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Vladimir Mikhalenko[1]*, Anna Kozachek[2], Janvarbi A. Ekba[3]
[1] Institute of Geography, Russian Academy of Sciences, Russia, 29 Staromonetny per., 119017 Moscow, Russia
***Corresponding author**; e-mail: mikhalenko@hotmail.com
[2] Arctic and Antarctic Research Institute, Russia, 38 Bering st., St. Petersburg, Russia
[3] Institute of Ecology, Abkhazian Academy of Sciences, 9 Marr st., 384900, Sukhum, Abkhazia

TRANSFORMATION OF THE INITIAL ISOTOPIC COMPOSITION OF PRECIPITATION IN CAVES OF THE SOUTH-WESTERN CAUCASUS

ABSTRACT. The paper presents preliminary results and interpretation from an ongoing research project in the Novy Afon and Abrskil caves of Abkhazia. The research have demonstrated that $\delta^{18}O$ and δD analyses of drip and ground waters in two caves in the South-Western Caucasian region allows to better understand interaction between isotopic composition of precipitation, soil, and vadose zone. Drip and ground water samples from the caves were compared with the present-day Global (GMWL) and the Local Meteoric Water Lines (LMWL). They fall along the GMWL and LMWL and are tied by equation $\delta D = 5.74\delta^{18}O - 6.98$ ($r^2 = 0.94$). Drip water isotopic composition is similar to that from lakes and pools. The incline of $\delta^{18}O - \delta D$ line differs from GMWL and LMWL. It reflects a possible result from secondary condensation and evaporation and water-rock interaction, and depends on the climate aridity level.

KEY WORDS: Caucasus, cave, isotopes, paleoclimate, ground water.

INTRODUCTION

Understanding of recent climate change, its regional patterns, origin, and prediction is currently a major scientific challenge. Networks of climatic proxies with annual resolution, covering the areas of continental scale, can provide data for statistical analyses and numerical modeling of past climate change and thereby improve climate projections for the future. Calcareous speleothems provide continuous paleoclimate records for 10^3–10^5 years. The most extensively used speleothem paleoclimate proxies are carbon and oxygen isotopes. Significant progress in using the stable isotopic composition in speleothems has been made in the past few decades [e.g., Affolter et al., 2014; Boop et al., 2014; Fairchild et al., 2006; McDermott, 2004 and references cited therein]. Recently, Vasil'chuk and Vasil'chuk [2011] summarized previous studies on the stable water isotopic composition of cave ice and have shown that $\delta^{18}O$ and δD analyses of the cave ice reflect the input isotopic signal of the local rain water. Numerous studies have been focused on monitoring changes of precipitation water isotopic composition due to interactions in the soil and vadose zone and within the caves [Petrella, Celico, 2013; Bradley et al., 2010; Barnes, Allison, 1988]. Some results [e.g., Cuthbert et al., 2014: Luo et al., 2013] were calibrated by meteorological records.

Here, we report the results of measurements of the stable isotopic composition of drip water, cave pool water, and rain water samples from the Novy Afon and Abrskil caves in Abkhazia. We have extended the approach by adding the groundwater isotope component and comparing it with the Caucasus mountain glacier isotope composition in order to understand the processes controlling drip water and ground water isotopic composition at the studied sites.

SITE BACKGROUND

Data of environmental and climatic change in Abkhazia are presented in dendrochronological, paleolimnological, glaciological, and speleological archives as well as in historical record of climatic events in the past. High-resolution paleoclimatic reconstructions are lacking for this area, but a number of similar reconstructions developed for the cross-border region of Northern Caucasus [Solomina et al., 2012, 2014; Dolgova et al., 2013] may be applied for the Abkhazia area. Karst systems are abundant in the region due to specific geological and tectonic conditions. Cave calcites and stalagmites, in particular, may contain valuable paleoclimatological information. We have selected two caves for our reconnaissance study in Abkhazia.

The study areas are located in the central and eastern parts of Abkhazia (Fig. 1). The two studied caves are the Novy Afon and the Abrskil. The sampling sites are shown in Figure 1.

The entire study area is located in the south-western part of the Greater Caucasus Range

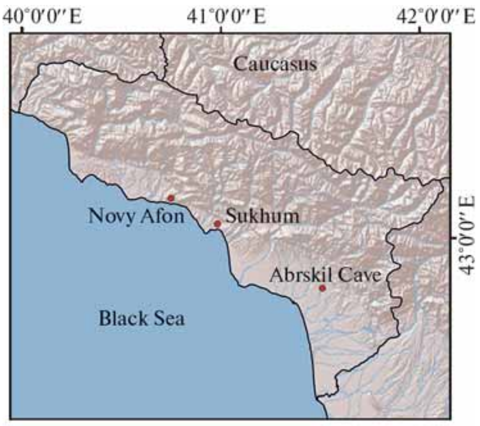

Fig. 1. Geographical location of sampling sites

(Fig. 1). The north-western and northern boundaries follow the Psou river-valley and the main ridge of the Greater Caucasus. Abkhazia has a joint border with Georgia on the east; it is bound by the Black Sea on the south and southwest. Its west-east and north-south extend is 170 km and 66 km, respectively, with the total area is 8665 км^2 [Ekba, Dbar, 2007]. The coastal range zone is situated between the marine plain and the belt of mid-mountain ranges located at the foothills and southern slopes of the Gagr, Bzyb, Abkhaz, and Kodor Ranges. Calcareous rocks and massive carbonates are widespread. This area is generally influenced by westerly circulation, however, the Greater Caucasian Range blocks penetration of cold air masses from the north. The mean annual air temperature at the Sukhum meteorological station (75 m a.s.l.) for the period 1904–2012 is 14.7 °C, while the mean winter (November–March) and summer (April–October) temperature is 7.0 °C and 22.7 °C, respectively. Mean annual precipitation for the same period is 1550 mm a^{-1} (870 mm a^{-1} in summer and 680 mm a^{-1} in winter).

KARST CAVES IN ABKHAZIA

More than 500 caves and carbonate caverns are located throughout Abkhazia [Tintilozov, 1976; Ekba, Dbar, 2007]. Abundant karst system and vauclusian springs are widespread near Mt. Iverskaya (344 m a.s.l.) and Mt. Novy Afon (500 m a.s.l.), and in the Psyrtsha river basin. The largest know Novy Afon (NA) cave and the underground Psyrtsha river represent the joint hydrogeological system. The cave is located in the interior of Mt. Iverskaya (344 m a.s.l.). The cave developed in the 300-meter depth Lower Cretaceous carbonates and was known from ancient times. It has been formed in the crest position of an anticlinal structure with permanent fold intensity and significant openness of fractures [Ekba, Dbar, 2007]. This cave system hosts abundant calcite dripstones many of which are currently actively forming. Considerable part of the NA cave has been recently adapted as a show cave for tourist activity. The cave entrance is situated at an elevation of 220 m. The total length of the cave passages is 3285 m, floor area is about 50 000 m^2, the height of the cave extension ranges between 15 and 67 m, the width varies from 20 to 70 m, and the total volume is $1.5 \cdot 10^6$ m^3 [Tintilozov, 1983].

Air exchange, defining the cave climatology, has been accelerated after the artificial tunnel and chamber construction. The approach of Ekba and Dbar (2007) provided for air ventilation in the NA cave that is influenced by air pressure at the surface of the karst massif. Air temperature measurements at the Novy Afon meteorological station show seasonal variations of average monthly temperature of 14–18 °C, while seasonal changes in the cave air temperature range between 0.2 and 1.2 °C for the 2004–2005 period. Temperature variability in the cave is within the range of 12.6–14.4 °C. Relative humidity in the cave was recorded over the 1970–1973 period; it varies from 98 to 100%, consistent with the cave ventilation and the outside air temperature.

The Abrskil cave is located in the eastern part of Abkhazia in the piedmont of the Panavsky Range (Fig. 1). The extension of explored part of the cave is 2700 m. The measured air temperature ranges from 12 to 14 °C.

SAMPLING SITES

Our monitoring research was undertaken at the Novy Afon and Abrskil caves in Abkhazia, South Western Caucasus (Fig. 1). Six samples were collected in the Novy Afon cave, including lake water, pool water, and drip water (Fig. 2). Also, drip water was collected in the Abrskil cave. Water isotopic composition of the Anakopia well water and rain water samples were analyzed for comparison with the cave water content.

The Anakopia well is located at the top of Mt. Iverskaya. The temple and the fort royal, awhile later, were built at the mount summit in the VI–VII centuries. They were mentioned in the medieval Georgian chronicle of the XI century where the battle with the Arabs in the 30s of the VIII century was reported. The temple was rebuilt several times; the last renovation was done by monks of the Novy Afon monastery in the beginning of the XX century when the ancient tanker well was cleared and reconstructed (http://afon-abkhazia.ru/). The well was cut in the rock and the pit of 1 m in diameter and 25 cm deep was found.

Rainfall water was sampled on September, 2014, in the on-shore area near Novy Afon at 5 m above sea level.

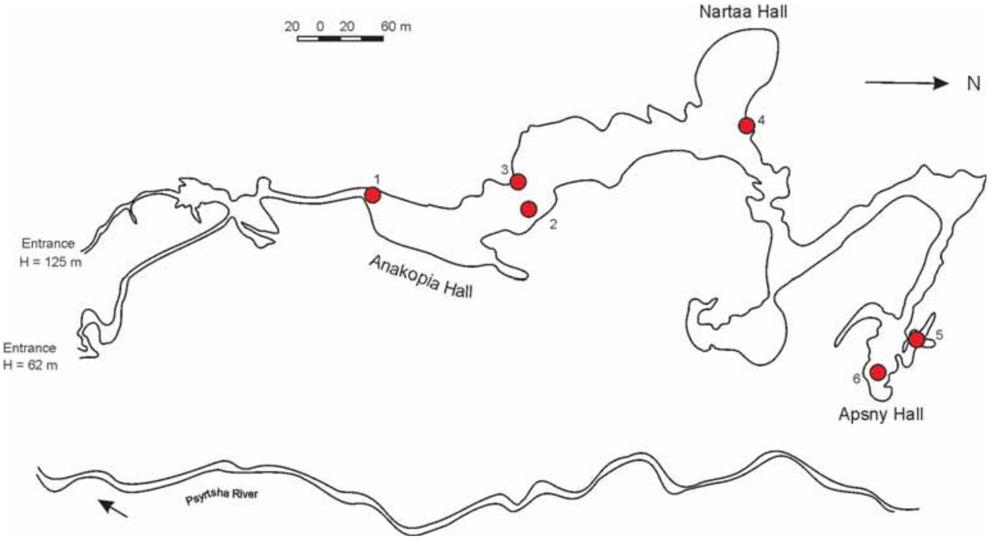

Fig. 2. Novy Afon Cave sampling locations (modified from: Tintilozov, 1983). Site numbers are given in Table 2.

METHODS

Drip and vadose waters as well as rainfall water were analyzed for the deuterium-hydrogen (D/H) and oxygen ($^{18}O/^{16}O$) isotope ratios using Picarro L1102-I instrument in the Climate and Environment Research Laboratory (CERL), Arctic and Antarctic Research Institute, St. Petersburg, Russia. To estimate precision of the measurements and to minimize memory effect associated with continuous measurements, the instrument was calibrated on a regular basis against isotopic standards V-SMOW, GISP, and SLAP provided by the International Atomic Energy Agency (IAEA). The estimated accuracy was ±0.05‰ for oxygen isotope ($\delta^{18}O$) and ±0.70‰ for deuterium (δD). The CERL laboratory working standard SPB was measured repeatedly following analysis of every 5 samples. The $\delta^{18}O$ and δD values were expressed in‰ units relative to the V-SMOW value.

RESULTS AND DISCUSSION

Isotopic composition of precipitation reflects the initial climatic signal. Evaporation of rainfall waters during infiltration into the upper vadose zone leads to their enrichment with heavy D and ^{18}O isotopes [Bar-Matthews et al., 1996; Ferronsky, 2015]. We are particularly interested in the mixture of isotopically modified rain waters and cave waters during stalagmite formation. The enrichment level of ground waters with heavy D and ^{18}O isotopes is the regional response and depends mainly on climate aridity. Independent study of isotopic composition of cave waters and precipitation is an essential component of cave speleothem research.

The use of oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic composition allows obtaining additional information on transformation of precipitation. On the global scale, this is represented by the global meteoric water line (GMWL) relationship: $\delta D = 8\delta^{18}O + 10$ [Craig, 1961]. It may vary in local and regional conditions. As for ground waters, the incline of the curve at $\delta^{18}O$ – δD diagram describes the level of postdepositional transformation in precipitation.

Currently, there are very few $\delta^{18}O$ – δD records available for the Caucasus [Vasil'chuk et al., 2006; Kutuzov et al., 2014] and these data have been obtained in glacierized areas. We included $\delta^{18}O$ – δD precipitation records derived at the GNIP (Global Network of Isotopes in Precipitation, IAEA) stations in the Caucasus and Black Sea region as well as snow and ice isotopic composition records from the Elbrus and Kazbek volcanic massifs (Table 1) in our study.

Figure 3a shows that δD and $\delta^{18}O$ data from precipitation and glacier ice plot near or on the bottom right of the GMWL from the isotopic data in the lowland sites (Batumi,

Table 1. The GNIP station and the Northern Caucasus water isotopic sampling sites.
For each site, $\delta D = a\,\delta^{18}O + b$ relationship is shown.
The source for the GNIP sites: http://www.univie.ac.at/cartography/project/wiser/gui/gnip

GNIP code	Country	Station name	Latitude	Longitude	Elevation, m	Period of observation	$\delta D = a\,\delta^{18}O + b$	R^2
3748400	Georgia	Batumi	41° 39′ 00″	41° 38′ 0″	6	1980–1990	y = 7,3519x + 9,1406	0,86
3752400	Georgia	Bakuriani	41° 42′ 36″	43° 30′ 36″	1665	2007–2009	y = 7,6565x + 11,311	0,98
3754900	Georgia	Tbilisi	41° 40′ 48″	44° 57′ 00″	490	1969–2009	y = 7,3339x + 6,0245	0,98
170260	Turkey	Sinop	42° 1′ 30″	35° 9′ 30″	32	1966–2009	y = 6,1343x – 1,2276	0,956
3473100	Russia	Rostov-na-Donu	47° 15′ 00″	39° 49′ 12″	77	1970–1990	y = 7,3843x + 3,0123	0,90
	Russia	Elbrus	43° 20′ 53.9″	42° 25′ 36.0″	5115	2012–2013	y = 7,8966x + 17,475	0,99
	Russia	Kazbek	42° 42,190′	44° 29,917′	4700	2013–2014	y = 8,0843x + 18,417	0,99

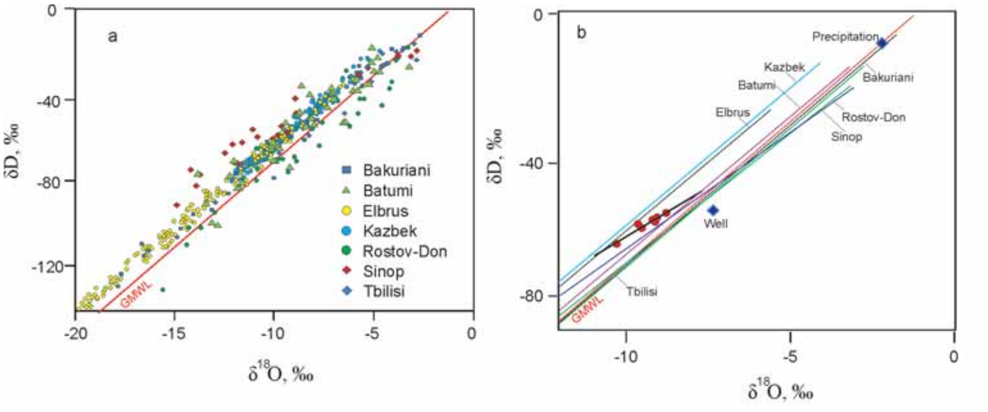

Fig. 3. (a) δD vs. δ18O for monthly precipitation at the GNIP stations and isotopic composition of the ice cores from the Caucasian glaciers. Global Meteoric Water Line (GMWL) (red line) is shown. (b) Trend lines of the data presented in (a): GMWL (red line) and δD vs. δ18O regressions for each site, drip water and ground water samples from the Novy Afon and Abrskil Caves (red circles) and δD vs. δ18O regression (black line), rainfall on September 9, 2014 and Anakopia Well samples (blue diamonds). Regression equations and correlation coefficients are presented in Table 1

Rostov-na-Donu), but near or on the top left in the mountain regions. McGarry et al. (2004) arrived at a similar result in the Eastern Mediterranean where the local meteoric water lines (LMWL) are ranged depending on air temperature and relative humidity. The δD and $\delta^{18}O$ record of rain precipitation collected on 9 September 2014 at sea level near the Novy Afon plots on the GMWL (blue diamond on Fig. 3b). The figure shows that isotopic composition of precipitation agrees completely with the regional pattern.

The $\delta^{18}O$ and δD values in all ground waters including drip water, cave lakes, and small pools vary within a rather small range from –10.23‰ to –8.88‰ and from –66.23‰ to –58.07‰, respectively (Table 2). Figure 3b demonstrates that the ground water samples fall along the GMWL and LMWLs with equation $\delta D = 5.74\ \delta^{18}O - 6.98$

Table 2. Water isotopic composition

Sample number	Location	$\delta^{18}O$,‰	δD,‰
1	N. Afon, Anakopia Hall, lake water	–9,64	–61,12
2	N. Afon, Anakopia Hall, pool water	–9,18	–60,38
3	N. Afon, Anakopia Hall, drip water	–8,88	–58,07
4	N. Afon, Nartaa Hall, lake water	–10,23	–66,23
5	N. Afon, Apsny Hall, drip water	–9,24	–59,75
6	N. Afon, Apsny Hall, pool water	–9,11	–59,33
7	Abrskil, drip water	–9,54	–61,93
8	Rainfall (09/09/14)	–2,24	–7,35
9	Anakopia Well	–8,27	–52,57

(r^2 = 0.94). Drip water isotopic composition is similar to that from lakes and pools. The incline of $\delta^{18}O - \delta D$ line differs from GMWL and LMWL. It reflects a possible result from secondary condensation and evaporation and water-rock interaction, and depends on climate aridity level. The value of the coefficient **a** in $\delta^{18}O - \delta D$ relationship is 2.9 ± 0.2 for extra arid conditions of Northern Africa [Gonfiantini et al., 1974]. It ranges from 4 to 6 for the cave waters in South East China and Western Australia [Couthbert et al., 2014; Luo et al., 2013]. However, McGarry et al. (2004) observed $\delta^{18}O - \delta D$ relationship in the Soreq cave, Israel, which is close to the Mediterranean Meteoric Water Line with a similar **a** coefficient.

This result shows the extent of atmospheric precipitation transformation under infiltration through the vadose zone in the south-west Caucasus. It is necessary to explore the reliability of this relationship in the annual and interannual cycle.

The δD and $\delta^{18}O$ composition of water in the Anakopia well at the top of Mt. Iverskaya shows (Fig. 3b, blue diamond) the discrepancy with the regional precipitation isotopic content. The water level in the well is permanent over the whole year; however, the drainage area is not sufficient for maintenance of the stable level because of rain water input. Isotopically, it is consistent with ground waters from the Novy Afon and Abrskil caves (see Table 2). This shows that cave and fault-line waters are considerably concerned with the Anakopia well water.

CONCLUSIONS AND FUTURE WORK

The speleothem water isotopic composition, originally sourced from precipitation, may change due to evaporation in the soil and vadose zone and in the caves. Transformation of the initial isotopic composition depends on climate aridity. At our monitoring sites, drip and ground waters were heavier than precipitation near the cave area and the weighted mean regional precipitation. Our first approach provides the basis for exploring the relationship between the speleothem water isotopic composition and the corresponding precipitation waters. However, many problems of the speleothem application as paleoclimate indicators have not been taken into account in our research. The oxygen isotopic composition in different drip waters within the same cave can be effected by hydrological processes and can differ from site to site. High temporal resolution drip rate monitoring has to be combined with monthly isotope drip water and rainfall sampling at the Novy Afon cave. It is necessary to explore monthly isotopic composition in precipitation and establish the relationship with air temperature. This would provide for interpretation of speleothem water isotopic records in terms of temperature changes at the surface.

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Vladimir Mikhalenko is a Senior Research Scientist at the Institute of Geography, Russian Academy of Sciences in Moscow. He received his Ph.D. degree in 1990 and D.Sc. degree in 2004 in glaciology. His research interests are associated with glacier mass balance, ice core drilling, and paleoclimatic reconstructions based on ice-core analysis. He participated in glaciological and ice core drilling projects in Antarctica, Greenland, Franz Josef Land, Svalbard, Bolivian and Peruvian Andes, Himalayas, Tibet, Kun Lun, New Guinea, Caucasus, Pamir, Tien Shan, Alaska, and Africa (Kilimanjaro). He is the author and co-author of more than 100 papers and 5 monographs.

Anna Kozachek obtained her Master degree in physical and evolutionary geography from the St. Petersburg State University in 2011. Since 2009, she has been Research Scientist in the Climate and Environmental Research Laboratory of the Arctic and Antarctic Research Institute (St. Petersburg, Russia). Her main research interests include isotopic composition of precipitation, snow and ice cores, and paleoclimatology.

Janvarbi A. Ekba is a Full Professor, Member of the Academy of Sciences of Abkhazia (ANA), Deputy Director of the Institute of Ecology ANA, Head of Applied Ecology Department at Abkhazian State University in Sukhum. His main research interests are geophysics, atmospheric physics, geoecology, and ecological geophysics. He received his Ph.D. degree in 1973 and D.Sc. degree in 1997 in atmospheric physics. He was Research Scientist and Head of Laboratory at the High-altitude Geophysical Institute in Nalchik in 1987–1998, Director of Geophysical Center in Stavropol, and Professor and Head of the Geophysical Department at Stavropol State University in 1996–1998. He is the author of 110 publications, including 3 monographs. Main publications: "Physics of atmospheric precipitation" (2001), "Introduction to environment research" (2002), "Ecological climatology and landscapes of Abkhazia" (2007).

Vladimir G. Konovalov
Institute of Geography, Russian Academy of Sciences; 29; Staromonetny per., 119017 Moscow Russia; tel: +7 499 1590603; fax: +7 495 9590033;
e-mail: vladgeo@gmail.com.

A NEW APPROACH TO ESTIMATE WATER OUTPUT FROM THE MOUNTAIN GLACIERS IN ASIA

ABSTRACT. Regional data on climate, river runoff and inventory of glaciers within High Mountainous Asia were used as informational basis to elaborate new approach in computing components of the hydrological cycle (glaciers runoff, evaporation, precipitation). In order to improve and optimize the calculation methodology, 4 675 homogeneous groups of glaciers were identified in the largest Asian river basins, i.e., Amu Darya, Syr Darya, Indus, Ganges, Brahmaputra, Tarim, and others. As the classification criteria for 53 225 glaciers located there, the author consistently used 8 gradations of orientation (azimuth) and 23 gradations of area. Calculating of the hydrological regime of glaciers was performed on the example of several Asian river basins. It has been shown that in the drainless basins in Asia, the only potential factor of the glacial influence on the changes in global Ocean level is the seasonal amount of evaporation from the melted surface of perennial ice and old firn. These results and published sources were used for re-evaluation of the previous conclusions on the influence of glacier runoff on change of the Ocean level. Comparison of measured and calculated annual river runoff, which was obtained by means of modeling the components of water-balance equation, showed good correspondence between these variables.

KEY WORDS: Asian river basins, generalization, glaciers runoff, water balance, Ocean level.

INTRODUCTION

Water resources of rivers in the Asian continent constitute a significant proportion of the total volume of the global fresh water resources. According to [World Water Resources, 2003], in terms of the basin area and the average annual runoff volume for the five major rivers, Asia is the second, after South America, in a group of five continents of the Earth (Africa, Asia, Europe, North America and South America). Asia is the first in terms of renewable water resources, and its contribution to the overall global volume equals 31.6% [World Water Resources, 2003]. The total area of world inland glaciation is 287 230 km^2 [Dyurgerov, 2002] and Asia's share of this amount is 42.0%.

The majority of the contemporary issues and problems are solving by glaciologists in many countries are directly connected with the study and description the regime of glaciers, which produce in Asia essential part of river runoff. The author uses the term "regime" in its definition by [Kotlyakov and Smolyarova, 1990]. Depending on the purpose and level of generalization of the initial information, researchers describe the diurnal, intra-annual, annual, and perennial temporal variations of glaciers and parameters of their regime. At this, the objects of study are components of regime in a separate point on the glacier, the whole area of individual glaciers, and aggregation of glaciers with different hierarchy. Typically, measured components of regime are available for a very limited number of individual glaciers. Data series contained many gaps, not evenly distributed in space, and often not comparable across time and in the composition of parameters. All this greatly hampers usage of direct measurements in assessments of regime of glaciers in mountain ranges or for entire river basins. Attempts to substitute the assessments of regime for the statistical population of glaciers with observations on individual "representative" or "reference" glaciers proved fruitless, as has been rightly pointed out in [Fountain et al, 2009], primarily because of the lack of a clear definition of representativeness and for many other reasons.

In the author's opinion, estimation of runoff volume from all glaciers in the large river basins or mountain regions may use limited number of mass balance measurements (now it varies between 250–300 for the whole Earth) only for calibration of local or regional physical relationships, used in mathematical models of hydrological regime. Suggested new method to determine water output from regional populations of mountain glaciers in Asia includes the following stages.

A. Separation of the Asian large rivers, from origins to mouth, into two main groups: (a) not drained to the Ocean or closed (e.g., Amu Darya, Syr Darya, Tarim) and (b) having direct inflow to the Ocean (e.g., Indus, Ganges, Brahmaputra).

B. Regionalization of separated large watersheds into sub-basins, depending on given applied tasks and quantity of initial hydrological, glaciological, and climatological information.

C. Generalization of glaciers in sub-basins into groups with similar sets of area-altitudinal parameters, which initially were extracted from available glacier inventories and obtained after processing of satellite images.

D. Development of model of glacier runoff as a component of annual water balance of a river basin, based on generalized information (see item C) and a set of hydrometeorological data.

E. Computation of the components of water balance (precipitation, evaporation, and glacier runoff) and evaluation of their quality and consistency to the measured river runoff; estimation the influence of these components on the change of the Ocean level.

OBJECTIVES OF THE RESEARCH

Main objectives of the research presented herein are: (a) introducing statistically substantiated new concept "characteristic groups of glaciers" instead of the current concept "sample of reference glaciers"; (b) using this new concept in modeling of the water output from regional populations of glaciers in the Asian river basins; (c) re-evaluation of the glaciers' contribution to the change of the Ocean level. Our study includes the following sections. 1. Spatial generalization the parameters of glaciation. 2. Informational base for calculating hydrological regime of the total glaciers' number in the river basins. 4. Model of calculating runoff, precipitation, and evaporation in the area of glaciation. 5. Application of the elaborated model and background information for estimation of the water balance components in the several Asian river basins.

MATERIAL AND METHODS

Spatial generalization of the glaciation parameters

Computational power of modern computers is enough to calculate the hydrological regime of all glaciers on the Earth as a function of climatic variables, results of cataloging, and dynamic characteristics of glaciation. The problem is that the current spatial resolution of the meteorological fields, especially in mountainous regions of Eurasia, is not sufficient to obtain the values of precipitation, solar radiation, air temperature, humidity, etc., which could be applied to the each individual glacier. Therefore, in order to get data on hydrological regime of all glaciers within large river basins, it is proposed to merge individual glaciers into quasi-homogeneous groups, according to the principle of uniformity characteristics of area, altitudinal, and morphological parameters of glaciation in each group. The input data in this case consists of morphometric parameters for all glaciers in the given population. The minimum set of input parameters includes the following: ID of the glacier, orientation (azimuth), absolute altitude of its beginning Zb, and end Ze, lower altitudinal boundary of the nourishment area Zf, geographic coordinates (Longitude, Latitude), and the total area of each glacier Fgl. This data set could be expanded.

Groups of glaciers and files of their calculated characteristics are formed using a special computer program, which performs double filtering of the initial data for glaciers in the river basin as a whole or its part: (a) first, we select a sets with the same orientation of glaciers. The number of such sets is eight for orientations N, NE, E, SE, S, SW, W, and NW. (b) then, in each of the eight sets, we identify groups of glacier with the area inside of one of the 23 intervals (see Table 1).

Determination of mean and mean-weighted on area parameters for glacier groups occurs automatically and is the final part of the second stage of data filtering. Eventually, all glaciers in the river basin or within a given mountain area are generalized maximally into 184 quasi-homogeneous groups; if in each of the eight sets are filled all 23 intervals of area. The output characteristics for each group in the case of minimum sets of input data are the following: orientation (azimuth), boundary values of the area intervals, number of glaciers that fall into each interval, weighted by the area average values of Ze, Zb, Zf, Longitude, Latitude, difference Δ= (Zb–Ze)/10, and 10 values of the altitude in the range of Zb–Ze with a step Δ, area of the glacier from Ze to Zf, and the total and average area of glaciers in the ranges 1–23.

As a result of averaging, the values of the altitudinal and areal parameters for groups become more reliable, which increases quality and representativeness of glaciological calculations. An example of generalization of 6 262 glaciers in the Vakhsh and the Panj river basins (origins of the Amu Darya river) into the 1 473 groups is shown in Fig. 1 a–b. Blue squares in the figure – are individual glaciers, black triangles – are groups of glaciers. In general, the number of generalized groups and their location is associated with allotment of specific parts in the river basin: the more parts, the more groups of glaciers and, hence, we obtain a more detailed spatial distribution of the generalized parameters of glaciers.

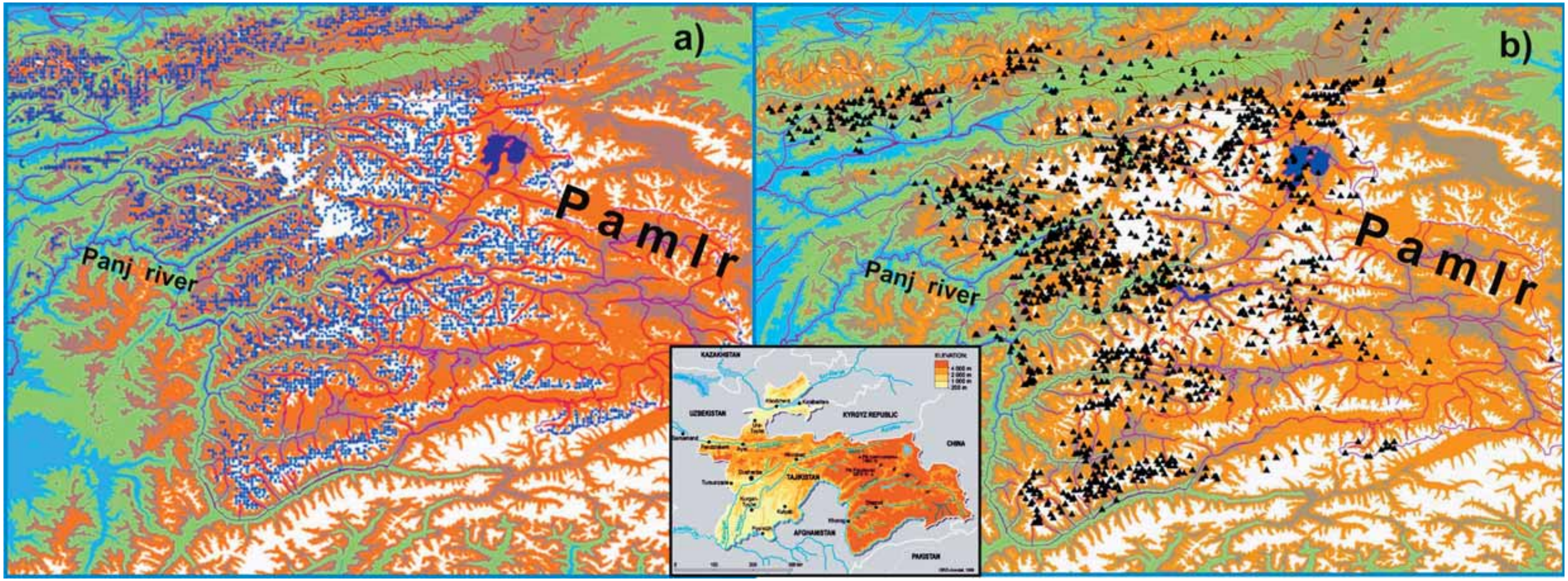
The quality of generalization of remote sensing data depends on the subjective and objective conditions of identification and digitizing glaciers on satellite images of glacial areas, as well as relates to the vertical and horizontal resolution of DEM. The negative impact of the subjective factor can be reduced by ensuring the employment of qualified experts and by using some service functions of the GOOGLE EARTH program for the purpose of identifying objects. The resolution power of the DEM SRTM3, available in the public domain, is 20 m horizontally and 16 m vertically at the 90% significance level [SRTM, 2003]. Analysis of the quality of SRTM3 has shown that application of this DEM correspond to the topographical maps of scale 1:50 000 [Jarvis et al, 2004].

Regionalization of the glacierized territory is one of the necessary stages in generalization

Table 1. Half-open intervals of area to identify homogeneous groups of glaciers in the eight sets of aspect

Numbers	Intervals of area in km^2							
1–8	(0; 0.1]	(0.1; 0.2]	(0.2; 0.3]	(0.3; 0.4]	(0.4; 0.5]	(0.5; 0.6]	(0.6; 0.7]	(0.7; 0.8]
9–16	(0.8; 0.9]	(0.9; 1.0]	(1.0; 1.5]	(1.5; 2.0]	(2.0; 2.5]	(2.5; 3.0]	(3.0; 4.0]	(4.0; 5.0]
17–23	(5.0; 6.0]	(6.0; 8.0]	(8.0; 10.0]	(10.0; 40.0]	(40.0; 70]	(70.0; 100]	> 100	

Note. A half-open interval means that variable x is inside of the limits a and b ($a < x \leqslant b$).



#Fig. 1.

a) Glaciation in the Vahsh and Panj river basins (origins of the Amu Darya river within the Pamir mountain region), ■ – means individual glaciers (N_{gl} = 6 262);.

b) Regionalization of glaciers in the Vahsh and Panj river basins, ▲ – means groups of glaciers (N_{gr} = 1 473).

a given aggregation of glaciers. Delineation of hydrological basins such as those in the former USSR Inventory [Vinoradov, et al, 1966] should be considered the most appropriate approach, because it allows using the water balance equation in the development and validation of hydrological and glaciological models. The same principle was used by [Shi Yafeng, et al, 2009] in structuring China's glaciation, initially for 10 hydrological territorial units and dividing them afterwards into 31, 102, 349, and 1462 separate sub-basins. Data in glacier catalogs and vector polygons of glaciers in each of these sub-basins are necessary and sufficient information in order to generalize glaciation into homogeneous groups and to determine the set of their morphometric parameters.

Characteristics of glaciers from the WGMS, Global Inventory of glaciers [WGI – World Glaciers Inventory, 2007] were used to prepare an expanded set of input data and calculation parameters for groups of glacier in the High-Mountain Asia. Brief results of this work are presented in Table 2, and detailed ones were used for comparative studies of the properties of glaciation and for calculation and prediction the glacier runoff [Agaltseva and Konovalov, 2005; Konovalov, 2006, 2007]. Location of large Asian river basins with these glacier groups illustrates Fig 2.

The spatial distribution of glacier parameters was analysed by using data for the following river basins representing a wide range of climatic conditions within the High-Mountain Asia: the Yurunkash river (`right tributary of the Tarim river), the Syr Darya river; tributaries of the Vakhsh river (Kyzylsu, Muksu, Obihingou, Surhob), the Brahmaputra river, tributaries of the Indus river (Astor, Beas, Jhelum, Ravi,

Table 2. Parameters of glaciation in the Central and High Mountain Asia

Region	River Basin	Ngl	Fgl km^2	Ngr
Asia	Vakhsh (4 basins)	2 012	3 361	500
Asia	Zeravshan	892	687	117
Asia	Panj (11 right side tributaries)	3 970	3 848	1 019
Asia	Syrdarya	3 429	2 522	148
Bhutan	Ganges tributaries	677	1 313	146
India	Indus tributaries (4 basins)	2 182	3 913	477
China	East Asia Basins	11 795	21 767	178
China	Central Asia basins	2 385	2 048	142
China	Kara Irtysh	403	289	90
China	Mekong	380	316	101
China	Ganges tributaries	13 006	18 100	173
China	Indus tributaries	2 032	1 451	134
China	Salween	2 021	1 730	145
China	Tibet	536	5 230	96
China	Yellow	121	130	56
China	Yangtze	1 324	1 893	148
Nepal	Ganges tributaries	3 252	5 322	435
Pakistan	Indus tributaries (6 basins)	2 808	7 223	570
	In total	53 225	81 144	4 675

Note. Ngl and Fgl are the number and area of glaciers by data of WGI from February 2012 and Concise Glacier Inventory of China, 2008; Ngr is the number of glacier groups generalized by the method described in this paper.

Fig. 2. High Mountain Asia river basins as objects of the research.

Sutlej, Chenab, Shayok, Shigar, Shingo), and tributaries of the Ganges river in Nepal and Bhutan. Processing was done for 27 698 glaciers with the total area of 43 981 km^2; 3 533 generalized groups were identified. By means of these data, were obtained characteristics of spatial distributions for the areal and altitudinal parameters in the glacier groups, based on the totality of glacier data in the considered region, but not on limited sample of so called "representative" glaciers.

We found that (a) for all orientations of glaciers and their area of up to 0.4 km^2, the minimum altitude (Ze) has a fairly close relationship with geographical longitude; (b) this dependence decreases linearly with the growth of area; (c) the minimum glacier altitude for all orientations and area of more than 40 km^2 has practically no relationship with geographical longitude; (d) similar dependences also revealed for the maximum glacier altitude (Zb), although with lower values of correlation coefficients; and (e) the spatial correlation of Zb and Ze with geographical latitude for all orientations and gradations of glacier area is significantly smaller than with longitude.

The distributions along longitude for average weighted values of minimal, mean, and maximal altitudes of glaciation and its area have also been obtained (Fig. 3) for the river basins of High-Mountain Asia. Distribution of altitudinal and areal parameters of glaciers are directly related to the problem of relationship between climate and glaciers, since to describe spatial distribution and calculate the climatic characteristics are also used geographic coordinates and altitude. We mean here two types of time-varying spatial distribution functions: (a) morphometric parameters of glacier groups and (b) main climate factors affecting the regime of glaciers (precipitation, air temperature) and establishing a link between these two functions of distribution.

Baseline data to study and describe regime of glaciers in river basins

Assessment of the hydrological regime of glacier groups was based on the regional and global data sources on hydrology, glacier parameters, precipitation, air temperature and humidity, clouds, and other influencing climatic factors (links to the sources of data are listed in References).

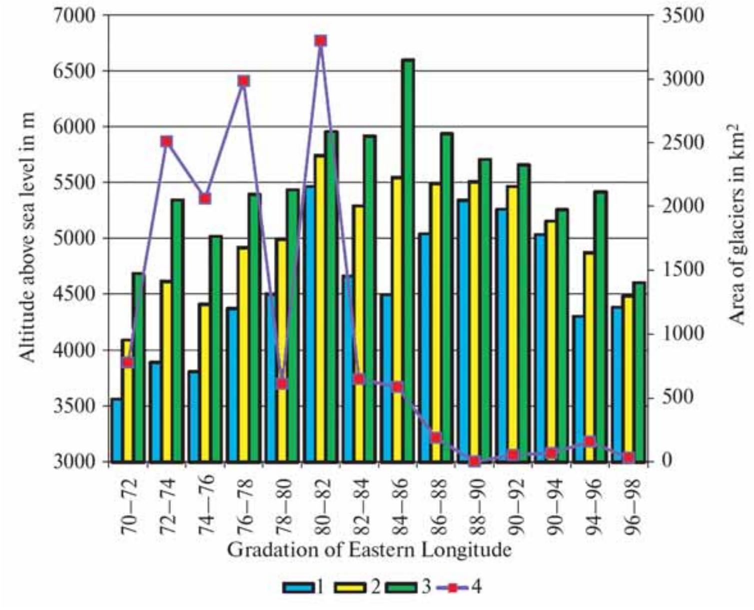


Fig. 3. Topography parameters of glaciation distributed along longitude within river basins of the High Mountain Asia. Aspects N, NE, NW are used.

1, 2, 3 – are respectively minimal, maximal, and average altitudes of glaciers' weighted by area, 4 – is area of glaciers

<u>Meteorological data.</u>

[Former Soviet Union Monthly Precipitation Archive, 1891–1993; GSOD (Global Summary of Day) 1929–2014; GHCN (Global Historical Climatology Network Database) v.2; CRU TS (Climate Research Unit Time Series) 3.0 1901–2006; WorldClim – Global Climate Data; Williams and Konovalov, 2007].

<u>Regional and global data on runoff.</u>

[GRDC (Global Runoff Data Center); Bodo, 2000]. This information includes data on runoff during the years 1881–1995 for 316 gauging stations from the archives of NCAR ds553.1 and for 2 134 gauging stations from the database of the State Hydrological Institute, Russian Federation.

<u>Regional and global data on glaciers.</u>

[WGI – World Glacier Inventory; GLIMS (Global Land Ice Measurements from Space); Fluctuation of Glaciers for 1959–2007; Catalog of the USSR glaciers, 1971–1978; Schetinnikov, 1997].

Preliminary assessment of the available initial data shows that their informational content and quantity is sufficient to calculate hydrological regime of glaciers in the High-Mountain Asia at the level of large river basins.

Methods of calculating runoff and evaporation in the area of glaciation

Unlike traditional studies on the specific values of heat and water-ice balance [e.g., Anderson, 1976; Cherkasov, 2004], we modeled and calculated the total runoff in the basin above a gauging site by means of independent evaluation of precipitation, evaporation, glacial runoff, and the dynamic water resources, as components of the annual river basin water balance equation. Statistical analysis of difference between calculated and measured runoff at gauging sites was used to assess the quality of calculations involving the water balance components.

The equation of the annual water balance for the river basins where runoff formed mainly due to snow and glaciers melting, has the form:

$$R = K_R(P - E + W_{gl}) + \Delta W \ \text{in km}^3, \tag{1}$$

where R is runoff, P is precipitation, Wgl is melting of perennial ice and firn resources, E is evaporation, ΔW is dynamic resources of water in the basin, K_R is coefficient transformation of the volume of water on the surface of a basin into river runoff. In equation (1) R – is a directly measured characteristic. In order to determine other components, we used different models and methods of calculation. Due to small variability of runoff during of low-flow period, its volume from January to March was accepted as estimation of ΔW value in equation (1).

The general form of the formula for calculating volumes of precipitation, evaporation, and other variables as one-dimensional function of altitude z in the range Zmin–Zmax, is:

$$X_2 = \int_{Z\min}^{Z\max} x(z)s(z)dz, \tag{2}$$

where $x = x(z)$ is a given function of altitude, $s(z)$ is distribution of area in the altitudinal range Zmin–Zmax. Applying the generalized mean value theorem in integral calculus to the integral of the product of functions $x(z)$ and $s(z)$, we obtain:

$$X_z = x(\tilde{z}) \int_{Z\min}^{Z\max} s(z)ds, \tag{3}$$

where $F = \int_{Z\min}^{Z\max} s(z)dz$ is area in the range Zmin–Zmax.

And finally:

$$X_z = x(\tilde{z})F, \tag{4}$$

or for the mean value $\overline{x} = x(\tilde{z})$, where $\tilde{z}$ is the certain elevation in the interval Zmin–Zmax. In [Borovikova et al, 1972] have shown that when $x(z)$ is approximated by a parabola, the form of a formula to determine the average value of x in the range Zmin–Zmax is:

$$\begin{aligned}\overline{x} &= x(z_0)[1 + k_2(\tilde{z} - z_0) + \\ &+ k_3(\tilde{z} - z_0)^2] + x(z_0)k_3\sigma_Z^2,\end{aligned} \tag{5}$$

And for the linear version of $x(z)$:

$$\overline{x} = x(z_0)\left[1 + k_2(\tilde{z} - z_0)\right], \tag{6}$$

where the first term in the right side of (5, 6) is equal to $x(\tilde{z})$ at using given value $\tilde{z}$ for elevation z, $x(z_0)$ – is known value of $x(z)$ at the elevation z_0, k_2 and k_3 are empirical coefficients, and σ_Z^2 is the variance of z in the range Zmin–Zmax. Thus, for any linear and quadratic functions $x(z)$, we have a strict equality between the average values of the dependent variable and its value at the weighted average elevation in the range Zmin–Zmax.

The physical-statistical model REGMOD for processes of accumulation and ablation of snow and ice in the glacial regions of Central Asia, as detailed in the works [Konovalov, 1985, 1994, 2006, 2007], is applied to determine Wgl.

A simplified version of the model REGMOD is based on application of the findings and conclusions in paragraphs 3.1, 3.3. Simplifications are as follows: (a) calculations of Wgl are performed only for the long-term average and extreme values of air temperature, evaporation, and precipitation in the watershed; (b) dependence of M on the average summer air temperature is used instead of melting rate M as a function of the absorbed solar radiation and air temperature; (c) morphometric parameters of glaciers are adopted invariant for the entire computing period, and (d) calculation of glacier runoff and evaporation is limited to the time interval June-August or the summer season.

In the long-term average case, according to equation (1) of water balance for the river basin, the glacial runoff forms within the area of each glacier from its end Ze to the elevation of firn boundary Zf. The author's model includes estimation of the following components of glacial runoff: melting snow, old firn, open ice, and ice under the moraine cover. Thus, the total melting of glacier is modeled as the sum of three components: M1 = M1(Ze – Zuml), M2 = M2(Zuml – Zf), M3 = M3(Zf – Zb). It is clear that in the absence of moraines, M1 = M1(Ze – Zf) and M2 = 0. Here, Zuml is the upper level of continuous distribution of the moraine cover. This important characteristic can be found from the formula (7).

$$\mathrm{Zuml} = \mathrm{Ze} + (\mathrm{Zf} - \mathrm{Ze})\Omega \qquad (7)$$

where Ω = Fmor/F(Zf). Fmor is the area of solid moraine, F(Zf) is the area of ablation zone and both of them are generalized parameters in the groups of glaciers. The sense of the expression (7) is obvious: the greater relative area of the moraine in the ablation zone, the higher level of moraine distribution in the altitudinal range Ze–Zf. Next, we determined the open ice area Fice in the range of altitudes Zuml – Zf : Fice = = F(Zf) – Fmor and the average elevation in this interval Zice = (Zuml + Zf) · 0.5. The formula for determining the average elevation from Ze to Zuml is similar: Zmor = = (Ze + Zuml) · 0.5. All altitudes: Ze, Zmor, Zuml, Zice, and Zf are averages weighted by the area, which used to determine volumes of melting in the groups of glaciers. As the estimation of Fmor is used the difference between the total and exposed areas of a glacier from the World Glaciers Inventory [WGI, 2007].

We calculated the annual precipitation and evaporation in (4) at the weighted average altitude of the catchment for the area above the measurement station of a runoff.

The working formulas to determine long term averaged volumes of glacial runoff Wgl (km^3) and evaporation Egl (km^3) in the i-th group of k-th glacial basin are as follows:

$$\mathrm{Wgl} = \mathrm{Wice} + \mathrm{Wmor} \qquad (8)$$

$$\mathrm{Wice}[i, k] = \mathrm{M1}(\mathrm{Zice}[i, k], \varphi[i, k], \lambda[i, k]) \cdot \mathrm{Fice}[i, k] \qquad (9)$$

$$\mathrm{Wmor}[i, k] = \mathrm{M2}(\mathrm{Zmor}[i, k], \varphi[i, k], \lambda[i, k]) \cdot \mathrm{Fmor}[i, k] \qquad (10)$$

$$\mathrm{M1}(\mathrm{Zice}[i, k], \varphi[i, k], \lambda[i, k]) = = (a \cdot \mathrm{Ts}(\mathrm{Zice}[i, k] + c[i, k]) \cdot \mathrm{Nice}[i, k] \qquad (11)$$

$$\mathrm{M2}(\mathrm{Zmor}[i, k], \varphi[i, k], \lambda[i, k]) = = (a \cdot \mathrm{Ts}(\mathrm{Zmor}[i, k] + c[i, k]) \cdot \mathrm{Nice}[i, k] \qquad (12)$$

in (11–12) a ~ const = 0.57; c[i, k] = = 0.26 · Z[i, k] – 0.33 · φ[i, k] + 0.09 · λ[i, k] + 6.72

$$\mathrm{Egl}[i, k] = e(\mathrm{Zgl}[i, k]) \cdot \mathrm{Fab}[i, k] \qquad (13)$$

$$e(\mathrm{Zgl}[i, k]) = f\{\mathrm{PE}(\mathrm{Zgl}[i, k]), X(\mathrm{Zgl}[i, k]), pv(\mathrm{Zgl}[i, k]), \mathrm{Ts}(\mathrm{Zgl}[i, k], \varphi[i, k], \lambda[i, k])\} \qquad (14)$$

$$\mathrm{Ts} = \mathrm{Ts}(Z[i, k], \lambda[i, k], \varphi[i, k]); \qquad (15)$$

$$X = X(Z[i, k], \lambda[i, k], \varphi[i, k]) \qquad (16)$$

$$pv = pv(Z[i, k], \lambda[i, k], \varphi[i, k]) \qquad (17)$$

here, M1 and M2 are the layers (in mm) of melting open (bare) ice and ice under moraine for Nice = 92–Nsnow days without precipitation during summer (June–August) in points Zice([i, k], φ[i, k], λ[i, k]) and Zmor([i, k], φ[i, k], λ[i, k]) with the coordinates φ – latitude, λ – longitude; Nsnow is the number of days with snow deposition, including the duration of its melting; β(Hc(Zmor[i, k]) is the attenuation function of melting ice under solid moraine of depth Hc at an altitude Zmor[i, k]; Zgl[i, k] is the weighted average elevation of the ablation zone; Fab is the area of ablation; Ts is the average air temperature during a summer; pv is the average partial pressure of water vapor in the air for summer at the same point, where the layers of melting M1 and M2 were determined; Zgl is the average elevation of the glacier; Egl[i, k] is the volume of summer evaporation from glacier area Fab[i, k]; e(Zgl[i, k]) is evaporation rate; PE is the largest possible value of evaporation under given conditions of moisture; X is the seasonal precipitation.

Spatial extrapolation of the temperature Ts and the water vapor pressure pv play a key role in simplified method of calculation Wgl and Egl. Depending on the availability of input data, calculation Ts(Z[i, k], φ[i, k], λ[i, k]) can be done in several ways.

1) A local linear extrapolation of the data $Ts(Z_0, \varphi_0, \lambda_0)$ at a basic weather station for the determination of Wgl and Egl:

$$Ts(Z[i,k], \varphi[i,k], \lambda[i,k]) = \\ = Ts(Z_0, \varphi_0, \lambda_0)[1 + k_1(Z - Z_0) + \\ + k_2(\varphi - \varphi_0) + k_3(\lambda - \lambda_0)] \quad (18)$$

2) A regional extrapolation and averaging of data from several weather stations. Application of the second method is expedient in the absence of local data on air temperature:

3) $Ts(Z[i,k], \varphi[i,k], \lambda[i,k]) = K_T - \gamma \cdot Z \quad (19)$

here, K_T, $k_1 - k_3$ are empirical parameters, γ is the vertical lapse rate of air temperature. The same approaches are acceptable for spatial extrapolation of the water vapor pressure pv.

The model of water output from a glacier area should also describe different conditions of runoff formation in the ablation and accumulation subareas. For this purpose may be used equation (20), which was obtained in [Konovalov, 1985] for the most typical features of runoff formation in ablation (Ab) and accumulation (Ac) subareas on the Asian glaciers

$$Wgl = Vm(Ab) + (Vm(Ac) - \\ - Vm(Ab)/3.5) \quad (20)$$

here Vm(Ab) and Vm(Ac) – are correspondingly the volumes of annual surficial ablation within Ab and Ac subareas of a glacier, diacritic symbol over Vm means long term averaging. Equation (20) is valid until Vm(Ac) > Vm(Ab)/3.5.

APPLICATION OF THE ELABORATED METHOD

Table 3 presents the averaged results of calculation of all components in the right side of equation (1) for 1961–1990 as an example in the Brahmaputra, Vakhsh, Zeravshan, Sokh, Isfairam, Akbura, and Pskem River basins. It is important that these basins have different total and glaciers area. Quality assessment of calculated precipitation, evaporation, and glaciers runoff was obtained by substituting values of P, E, and Wgl in the equation (1) and comparing right and left sides of the annual water balance equation. In Table 3, we see that the difference between measured Rm and calculated Rc river runoff is rather small. This is a confirmation of the fact that the model and methods used in our research are of sufficiently good quality and could be applied in the Asian river basins for determining components in the right side of equation (1). However, it is true only if there is sufficient and reliable input information for equations (4–20); the most important are the data on precipitation. As it is well known, the unresolved uncertainty in estimation of areal precipitation is the main obstacle in applying climate models of different scales. Negative difference dR in Table 3 between the measured and calculated values of river runoff is explained well by water intake for irrigation and hydropower water reservoirs above the used gorging site. In the considered river basins according to AQUASTAT: http://www.fao.org/nr/water/aquastat/, which is FAO's global water information system, water intake for irrigation varies from 2–3% to 10–15% of the annual river runoff. Besides, there is the Papanskoe irrigation water reservoir with area of 7.1 km^2 and capacity of 260 mln m^3 located in the Akbura river basin above the Tuleken gorging site (gs). From the same information system and in [Rahaman & Varis, 2009] we see that similar irrigation water reservoirs located in the transboundary Brahmaputra river basin distort the natural regime of runoff above the Pandu gs.

Table 3. Annual water balance for some Asian river basins (mean values for 1961–1990)

River	gs	Long	Lat	Alt,	Fbas	Fgl	Rm	R(I–III)	P	E	Wgl	Rc	dR	dR	E/P	η
		grad, E	grad, N	m a.s.l.	km^2	km^3	%									
Brahmaputra	Pandu	72.52	40.24	3 384	405 000	14 113	574	40	719	162	41	639	–65	–11.3	22.5	0.80
Vakhsh	Komsomolabad	71.68	39.17	3 600	29 500	3 824	18.85	1.37	26.3	11.1	3.21	19.81	–0.96	–5.1	42.2	0.72
Zeravshan	Dupuli	67.48	39.29	3 100	10 200	674	4.84	0.30	11.1	4.73	0.34	4.95	–0.11	–2.3	42.7	0.42
Sokh	Sarykanda	71.13	39.95	3 030	2 480	252	1.38	0.08	2.0	1.11	0.33	1.51	–0.13	–9.4	56.2	0.70
Isfairam	Uchkorgon	72.05	40.11	3 240	2 200	102	0.66	0.09	1.3	0.84	0.13	0.69	–0.03	–4.5	64.1	0.50
Akbura	Tuleken	72.52	40.24	3 030	2 430	114	0.63	0.06	1.5	0.99	0.19	0.73	–0.10	–15.9	67.8	0.43
Pskem	Mullola	70.20	41.77	2 690	2 540	125	2.52	0.20	3.2	0.84	0.22	2.75	–0.23	–9.1	26.7	0.80

Note. gs – gorging site, Long, Lat – correspondingly geographical coordinates in decimal degrees, Alt – altitude above sea level, Fbas – basin area above gs, Fgl – glacier area in the basin, Rm –annual river runoff, measured at the gs, R(I–III) –volume of river runoff during January–March at the gs, P – annual sum of precipitation in the basin, E – total sum of evaporation, Wgl – annual glacier runoff, Rc – annual river runoff calculated aby the equation (1), dR – difference between Rm and Rc, η = Rm/P – runoff coefficient.

GLACIER RUNOFF AND THE OCEAN LEVEL

All continental glaciers, ice caps, and ice sheets should be hydrologically differentiated as: (1) marine-terminated, (2) not marine-terminated but having connection to the World Ocean through the river flow, and (3) not marine-terminated and located in closed river basins (not drained to the World Ocean). Simple and rather informative parameter of glaciers contribution to the level of World Ocean could be volume of inflow Vin being determined by formula Vin = μWgl. The coefficient μ is a full analog of coefficient runoff η in formula Rm = ηP (see Table 3), which shows that only certain part of precipitation P could be transformed into river flow. This is well-known and used without exception in hydrological calculations and no explanation exists why all contemporary determinations of Vin (e.g., IPCC 5-th Report) do not include coefficient μ. According to the three types of hydrological differences, which are identified above and depending on the distance between river mouth and location of glaciers, may be applied the next approximate values of coefficient μ: (1) 0.9–1.0; (2) 0.3–0.6; (3) 0.0–0.1. Surely, the spatial distribution of μ has to be studied. Since the coefficient μ was not included in the estimations of past, current, and future contribution of glaciers runoff to the level of World Ocean contained in the IPCC 5-th Report [IPCC, Climate Change 2013] and many other relevant publications, these results have to be revised only on this reason.

The other even more important reason is quality and representativeness of direct measurements of annual mass balance for very limited and random samples of so-called "typical" glaciers, which are used for global estimation of change the World Ocean Level under influence of glacier runoff. The representativeness of such "typical" glaciers regarding to the relevant general population is not proved. Besides, usage of the limited number of data on "typical" or "reference" glaciers for broad regional or global synthesis inevitably leads to uncertainty in these conclusions. For example, our processing of data in the Supplementary to Bahr et al [2009] revealed that average, maximal, and minimal completeness (in %) of mass balance measurements by years was as follows: for Asia and Caucasus, 28.4, 45.2, and 2.4 (42 glaciers during 1957–2000); for Europe, 26.8, 52.0, and 2.0 (100 glaciers during 1946–2003); and for America` 27.8, 50.7, and 1.5 (69 glaciers during 1953–2004). Thus, during of long-term period only around 30%, on average, of not synchronized and essentially unevenly distributed mass balance data were available and used for global conclusions. In, Bahr, et al. [2009], Dyurgerov [2010], IPCC 5-th report [2013], and in other publications, it is believed that all the glaciers provide drainage to the Ocean, though, for example, in Eurasia, the number, area and volume of glaciers' not drained basins is 57%, 56% and 62% of the total glaciation, respectively. Also, published calculations (e.g., IPCC 5-th report [2013]) lack independent verification by means of water balance equation of the influence of glacial runoff on the Ocean level.

The impact of glaciation on the volume of annual or seasonal runoff is inversely proportional to the distance from origins to mouth of the rivers. For example, relative contribution of glacial runoff in the mouths of the major Siberian rivers Ob, Yenisei, Lena, and Indigirka equals to, respectively: 0.6–0.7%, 0.03%, 0.02%, and 0.75% of the annual river runoff. According to calculations made by Krenke [1982], the norm of runoff from melting of the long-term resources of ice and firn of all glaciers within of the former Soviet Union was 24.1 km^3. Of this amount, the Ocean has received 14.58 km^3 (60.5%) and 9.52 km^3 was left in drainless basins.

Even at the maximum overestimation of the global glacial runoff made by Meier and Dyurgerov [2007], its average annual volume for 1961–2003 amounted to only 1.8–1.9% of the annual inflow to the Ocean from continental rivers of the Earth. Obviously, in such proportions of these components of the hydrological cycle and a very low long-term variability of the annual river runoff, it does not make sense to consider the contribution of the glacier component in the change of the Ocean level, as rightly noted by Malinin [2009]. Undoubtedly, the actual water output from all continental glaciers is at least half of the value proposed by Meier and Dyurgerov [2007].

Our statistical processing of data in World Water Balance [1974] showed that the coefficient of correlation between the Ocean level and the annual inflow there from rivers in Europe and Eurasia varies from –0.30 to 0.09 and the coefficient of variation for inflow of the same rivers changes from 0.04 to 0.20. At the same time, the coefficient of variation of the Ocean level was 2.23, which is much greater than the variability of the annual river runoff in Europe and Eurasia.

Thus, glacial runoff, which forms in different types of river basins, influences the Ocean level to a much lower degree than is described previously in the 5-th IPCC report [IPCC. Climate Change, 2013], Dyurgerov and Meier, [2007], Bahr, et al. [2009], and Dyurgerov [2010].

DISCUSSION

Rather than using the concept of "typical" or "reference" glaciers, our method, described in our research takes into account the peculiarities of the spatial distribution of all glaciers in a large river basin and can serve as a basis for essential improving of future glaciological and hydrological calculations. In this method, the quality of generalization for glacier parameters is not related to the subjective decisions of researchers and depends only on the completeness and reliability of the data sources. An extensive set of parameters obtained for the characteristic groups of glaciers is a sufficient basis for a comparative analysis of morphometry of glaciers and modeling components of hydrological cycle.

Here is necessary to emphasize that a broad application of the suggested method to measure, model, and calculate all components of equation (1) depends strongly on availability to operate at the regional scale with representative and reliable data on runoff, precipitation, air temperature, vapor pressure in the air, and area-altitudinal parameters of glacier. For example, measurements of river runoff should relate to rather large area of a glacierized watershed and should not be distorted by irrigational water intake.

Calculations by formulas (15–17) reflecting the dependence of precipitation, air temperature, and water vapor in the air on the altitude and geographic coordinates will be successful if original meteorological data cover or approach the range of altitudes where the glaciers are located. The number of meteorological stations is very limited in the upper watersheds of the rivers in the territory of the Himalayas, the Hindu Kush, and the Tibet. In this situation, in order to obtain formulas (15–17), we should use information from the regional and global climate databases: APHRODITE [Yatagai et al, 2012], CRU [CRU Datasets – CRU TS Time-Series, 1901–2009], GPCC: http://gpcc.dwd.de, UDEL [Willmott and Matsuura, 1995], WORLDCLIM:http://www.worldclim.org/current and others. If several empirical formulas for the same function are obtained, we may choose the most suitable expression for minimizing the difference between the measured and calculated runoff according to equation (1).

CONCLUSIONS

Determination of glaciers runoff is required for meso- and macro-trend analysis of the evolution of glaciation, in the study of similarities and differences of glacial complexes, and in solving problems related to water use, runoff forecasts, and sustainable development of mountain areas at the river basin scale. Specifics of the considered problem lies in the fact that the components of the annual water balance for the whole glacial areas can only be obtained by computational methods. This places high demands on the initial information, validity and spatial applicability of main applied decisions in mathematical modeling of runoff in glacierized basins. This statement agrees well with the conclusion made in [Cryosphere Theme Report, 2007] that updated methodology for estimating mass balance of glaciers should be based on meteorological data, in synergy with remote sensing data, to give a more comprehensive picture of mass balance in various climate zones and globally.

Assessments of the components of the water balance should be seen as a stage in a multifaceted system of description and prediction the long-term regime of rivers fed by snow and ice melting.

The methods used in our research to calculate the annual amount of precipitation, evaporation, glacier runoff, and dynamic water reserves are sufficiently reliable and suitable for other basins in the Central Asia with a similar type of runoff formation, as these methods provide quality of calculated river runoff, which is comparable with its measurements.

Application of generalized areal and altitudinal parameters for groups of glaciers has improved spatial extrapolation the climatic factors of runoff and has allowed comparison of parameters of hydrological regime of glaciers in different river basins.

This paper suggests a new method on regionalization of glacier populations and presents examples of its application in the Asian river basins. It demonstrates a new potential for the objective description of the spatial distribution of the areal-altitudinal parameters of glaciers and for usage of this information in statistically substantiated glaciological and hydrological models and computations.

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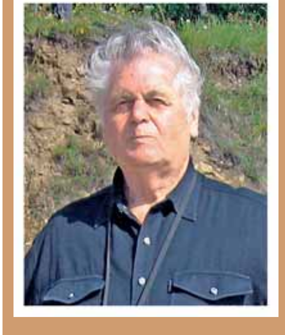

Vladimir G. Konovalov graduated from the Faculty of Geography at the Tashkent State University (physical geography) in 1959; he obtained his PhD degree (qualified in hydrology and glaciology) from the Faculty of Geography at the Leningrad State University in 1964. Dr. Konovalov received his D.Sc. degree in 1983 from the Institute of Geography (Irkutsk), USSR Academy of Sciences (Title of the Thesis "Processes of melting and runoff for the glaciers in the Central Asian watersheds"). Currently, Dr. V.G. Konovalov is Leading Scientific Investigator of the Department of Glaciology at the Institute of Geography (Moscow), Russian Academy of Sciences. He is Principal Investigator of a number of Scientific Projects and a member of Scientific Societies: Russian Geographical, International Glaciological, and Hydrological. Dr. Konovalov's area of professional experience includes also fieldworks in the Pamir and Tien-Shan mountain regions. He published nearly 135 scientific papers, including four monographs, and made presentations at many international and national symposiums, conferences, and workshops.

Dharmaveer Singh[1]*, Sanjay K.Jain[2], R.D.Gupta[3]
[1] GIS Cell, Motilal Nehru National Institute of Technology Allahabad – 211004, (India)
***Corresponding author:** e-mail: veermnnnit@gmail.com
[2] Water Resources Systems Division, National Institute of Hydrology, Roorkee – 247667 (India), e-mail: sanjay.nih@nih.ernet.in
[3] Department of Civil Engineering, Motilal Nehru National Institute of Technology, Allahabad – 211004, Uttar Pradesh (India), e-mail: gupta.rdg@gmail.com

GLOBAL CLIMATE MODEL: A COMPREHENSIVE TOOL IN CLIMATE CHANGE IMPACT STUDIES

ABSTRACT. There is growing concern, how and to what extent future changes in climate will affect human society and natural environments. Continuous emissions of Green House Gasses (GHGs) at or above current rates will cause further warming. This, in turn, may modify global climate system during 21st century that very likely would have larger impacts than those observed during 20th century. At present, Global Climate Models (GCMs) are only the most reliable tools available for studying behaviour of the climate system. This paper presents a comprehensive review of GCMs including their development and applications in climate change impacts studies. Following a discussion of the limitations of GCMs at regional and local scales, different approaches of downscaling are discussed in detail.

KEY WORDS: Climate, Green House Gasses, Global Climate Models

INTRODUCTION

Significant increase in concentration of Green House Gases (GHGs) *i.e.* carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and aerosols in the Earth's atmosphere was found in Post-Industrial Revolution era due to burning of fossil fuels, deforestation and land use practices [Loaiciga *et al.*, 1996]. In 1750 AD, the concentrations of CO_2, CH_4 and N_2O were 280 ppm, 715 ppb and 270 ppb whereas in 2005, these were 379 ppm, 1774 ppb and 319 ppb respectively. The increase in GHGs occurred more rapidly after 1950s as 70% of such increase is reported in between 1970 to 2004. The increased concentrations of GHGs in atmosphere have altered global energy balance and resulted into warming of the atmosphere. This in turn raised surface temperature and attributed to climate change [IPCC, 2007].

Natural resources and ecological resources of the Earth including human are greatly affected by climate change occurred in the recent past [Kislov et al., 2009]. It not only altered phenological development of flora but also caused extinctions of several species of flora and fauna. However, some species are still in danger. According to Hartmann et al [2013] human society witnessed huge loss of lives, mental and emotional distress, extensive damages to crops and properties due to changes in key climatic variables and related phenomenon.

There is growing concern, how and to what extent future changes in climate will affect human society and natural environments. Definitely, continuous GHGs emissions at or above current rates will cause further warming. This, in turn, may modify global climate system during 21st century that very likely would have larger impacts than those observed during 20th century. Global Climate Models (GCMs) sometimes also referred as General Circulation Models or coupled

Atmosphere Ocean Global Climate Models (AOGCMs) are currently the most reliable tools available for studying behaviour of the climate system, its components and their interactions and for deriving projections of meteorological variables [Hewitson and Crane, 1996; Solaiman, 2011]. These models are based on physical laws of radiative transfer and thermodynamic. They are run for accounting effect of GHGs and aerosols in the atmosphere and used to investigate anticipated behaviour of complex atmosphere-land-ocean systems under changing climatic conditions.

This paper presents an overview of GCMs in climate change impacts studies. The origin and stages in development of GCMs is described in section 2. Section 3 starts with the applications of GCMs in climate change studies including their limitations. Need of downscaling along with different downscaling techniques is addressed in section 4. Conclusion drawn from this study is presented in section 5 respectively.

ORIGIN AND STAGES IN DEVELOPMENT OF GCMS

The first GCMs developed in the 1960s based on work of Phillips (1956) and many others were simple Atmospheric Global Climate Models (AGCMs) [Barry and Carleton, 2001]. They were used to simulate average synoptic-scale (*i.e.* 10^4–10^6 km^2 spatial scale) atmospheric circulation patterns for specified external forcing conditions. The growing computational power of digital computers along with improved algorithms and understanding of the climate system has notably enhanced the modelling capability of GCMs. The chronological developments of GCMs are illustrated in Fig. 1. During mid 1980s, atmospheric and land components of the climate system were integrated in GCMs. Similar to AGCMs, Oceanic Global Climate Models (OGCMs) were also developed during this period. The late 1990s was an important phase in the history of GCMs where AGCMs and OGCMs were coupled and complex coupled Atmosphere Ocean Global Climate Models (AOGCMs) or simply abbreviated as GCMs came into picture. Incorporating all components of climate systems and their feedback interactions in GCMs have always been a challenge however, to the some extent these problems are solved in present days GCMs [IPCC, 2001]. They are designed to incorporate complex biogeochemical feedbacks (for example, carbon cycle, sulphate aerosols, non sulphate aerosols etc.) which determine the atmospheric composition and the nature of the land vegetation in addition to the major components (atmosphere, land, ocean, cryosphere and biosphere) of the climate systems.

AGCMs which explicitly account dynamical processes of the atmosphere simulate atmospheric processes in three dimensions (3D). Fundamental physical laws; conservation of energy, mass, and momentum are used to depict behaviour of the atmosphere. This includes derivation of a series of non-linear prognostic equations that are solved to obtain a trajectory of the global climate compatible with the external forcings under given initial conditions [Barry and Carleton, 2001]. The earth's surface (globe) is divided into a series of grid boxes (1° to 4°), extending vertically into the atmosphere. The size and number of the grid boxes are limited by the amount of computer power available and the time period over which the model is integrated [Hartmann, 1994]. Further, atmosphere is divided into different vertical layers (commonly 10–20) based on height or pressure levels with more levels near the earth's surface. Equations are solved at each grid point and at each vertical level at a preset time interval (typically 20–30 min) with vertical and horizontal exchanges of energy, mass, and momentum computed for all points at each time interval [Bradley, 1999].

There are some physical processes often called sub-grid scale processes (*e.g.* cumulus convection, surface heat and moisture fluxes, and terrain-induced vertical motion) occur at scales much smaller than the grid resolution and so cannot be explicitly simulated

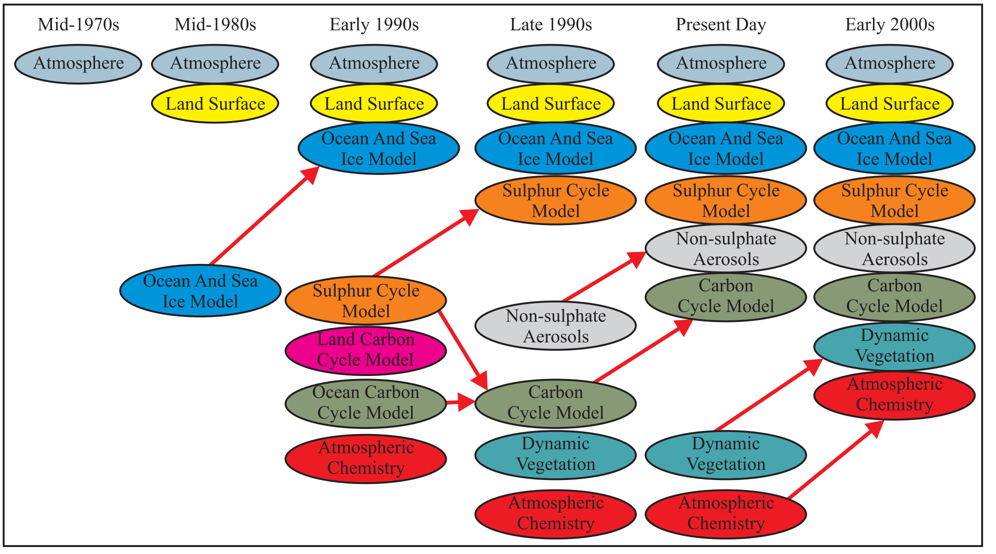

Fig. 1. Chronological development in Global Climate Models [IPCC, 2001]

[Hartmann, 1994]. Further, these unresolved sub-grid scale processes or phenomenon are parameterized accounting knowledge of the state of the atmosphere at the grid scale by means of simple mathematical relationships [McGuffie and Henderson-Sellers, 1997]. Uncertainty involved in parameterizations of these processes determines the behaviour of the climate model.

Oceanic Global Climate Models or Ocean General Circulation Models (OGCMs) are constructed by applying the same basic techniques used for AGCMs. They assume fixed wind stress, air temperature, air humidity, precipitation and radiative forcing. Together these determined the flux of momentum, heat, and freshwater at the surface that are the key driving forces of the ocean circulation However, their development has been lagged behind AGCMs and this has been attributed to non availability of observed records of oceanic parameters (sea surface temperature, salinity *etc.*) and computational problems required in simulation of oceanic processes [Hartmann, 1994].

The speed of many important ocean currents is small and therefore difficult to observe with great precision. Therefore, finer spatial resolution is required to simulate effectively the important scale of motion (oceanic eddies) that are < 50 km across [Bradley, 1999]. Besides, OGCMs attain a state of stable climatology after very long time integration because the deep circulation in the oceans requires centuries to spin up from rest or to respond to changed forcings. As a result, this long integration time and the high spatial resolution required for realistic simulations of ocean circulation require substantial and sophisticated computer resources for modelling [Hartmann, 1994]. These problem can be resolved by using a series of parallel computers (employing > 100 processors simultaneously).

Coupling of AGCMs and OGCMs

Coupling of AGCMs and OGCMs may be performed in four ways depending upon the complexity involved in exchange of heat and moisture [Bradley, 1999]. It has been shown in Fig. 2. In first level (simple coupling), surface temperature of the ocean is set and the ocean region ('swamp ocean') of the model interacts with the atmosphere only in terms of moisture exchange. In second

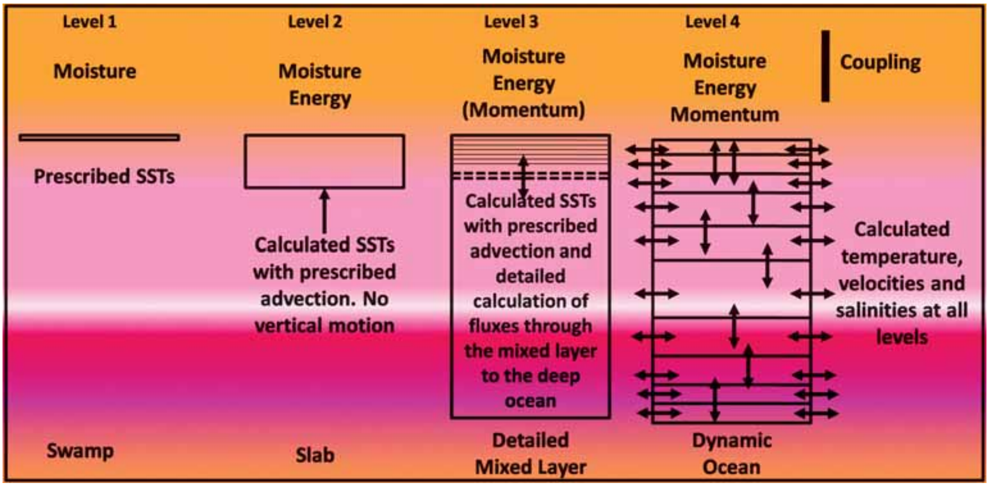

Fig. 2. Coupling with atmosphere in various types of ocean model [McGuffie and Henderson-Sellers, 1997]

level, exchange of both heat and moisture occurs with the atmosphere from a 'slab ocean' that has been specified as a layer of fixed depth (50–100 m). This mechanism of heat and moisture exchange enables Seas Surface Temperature (SSTs) to vary as the model run progresses. The nonexistence of vertical motion in such models restricts the exchange of heat from the deep ocean and merely exchange of horizontal energy fluxes occur. The mixed layer ocean (third level) is a further improvement, also involving prescribed horizontal advection, but with computation of fluxes to and from the deep ocean. In fourth level (fully developed coupled GCMs), the ocean has internal dynamics in three dimensions with calculated temperature, velocity and salinity in all directions. Further, exchanges of energy, moisture, and momentum take place at the ocean-atmosphere interface.

The major problem encountered in coupling of atmospheric and oceanic processes is large differences in estimated response times for different components of the climate systems (Fig. 3). The estimated response times for the atmosphere, surface snow and ice, litho-biosphere and lakes have been found in the range of 10^5s to 10^6s. Conversely, glaciers, ice sheets and the deep ocean have response times of order 10^9s to 10^{11-12}s respectively. The problem of mismatch in scale of response times is resolved by coupling models of each system 'asynchronously'. It involves operation of an atmospheric model for a time appropriate for that system and then uses the resulting atmospheric conditions as input to a model of the system operating on a different timescale [Bradley, 1999].

The coupled GCMs inherit substantial errors (transfer of errors from both the component) in the simulation of sea-surface temperature and sea ice extents. So, they are unable to simulate present climate accurately. This problem has been fixed by a technique known as flux correction or flux adjustment. Flux adjustments that are non-physical in nature are explicitly added in the models to give a stable and realistic simulation of present surface climate (especially the sea surface temperature and sea ice cover). These adjustments are considered as poor solutions in the validation process because they have introduced model uncertainties and violated the physical laws of conservation of mass and energy. However, the newest generation of GCMs has eliminated the need for flux adjustment [IPCC, 2001].

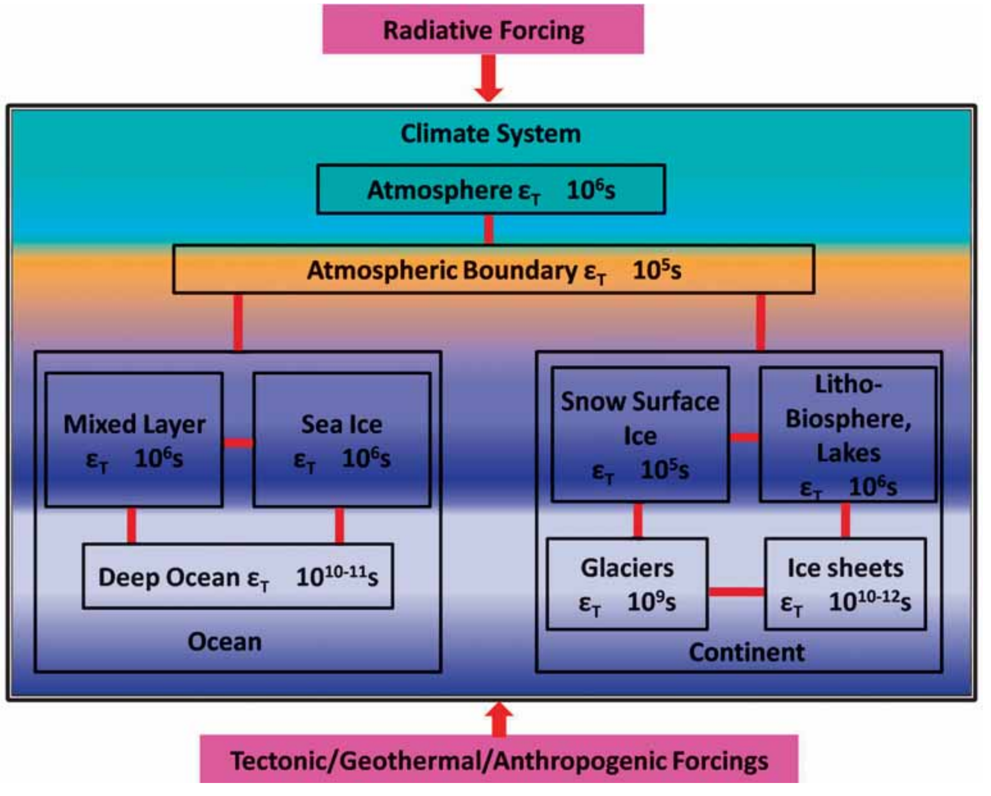

Fig. 3. Estimated response for different components of climate system [Saltzman, 1985]

GCMs and Emission Scenarios

After a model (GCM) is developed and validated, it can be used to evaluate alternative scenarios. Scenarios are alternative images of how the future might unfold. They have been generated based on certain assumptions (future trends in energy demand, emissions of GHGs, land use change and the behavior of the climate system over long time scales) for explicit use in investigating the likely consequence of anthropogenic climate change [IPCC, 2001]. IPCC which had initially used four man made future emission scenarios in its First Assessment Report (AR1), presented six alternative scenarios ranging from IS92a to IS92f in 1992. These scenarios embodied wide array of assumptions affecting how future GHGs emission might evolve. Out of these scenarios IS92a (Business as Usual) was widely adopted by the scientific community. In the light of improved understanding of climate dynamics and driving forces of emissions, these scenarios were re-evaluated and led to the release of Special Report on Emission Scenarios (SRES) in year 2000. Based on this report, a new set of scenarios was developed with four story lines (families) *i.e.* A1, A2, B1 and B2 to represent the range of driving forces and emission in the scenario literature. They reflect current understanding and knowledge about underlying uncertainties. However, in year 2013 IPCC replaced SRES scenarios with four Representative Concentration Pathways (RCPs) [IPCC, 2013]. These are RCP2.6, RCP4.5, RCP6.0 and RCP8.5 respectively. They are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6 W/m^2, +4.5 W/m^2, +6.0 W/m^2 and +8.5 W/m^2) [Urich *et al.*, 2014].

The requirements of large computational powers (super computers) have restricted their expansion only to the few research organisations or groups. However, notable increase in number of such research organizations is observed with successive IPCC assessments. Starting with five groups and eight models in 1990 (First Assessment Report), it has increased to 27 groups and 61 models in 2014 (Fifth Assessment Report) [Urich *et al.*, 2014]. These GCMs have been used to simulation the climate of 20th century (known as 20th Century Climate in Coupled Models (20C3M) experiment) and project several marker scenarios for the future based on IPCC SRES. Coupled Model Intercomparison Project Phase 3 (CMIP3) and Coupled Model Intercomparison Project Phase 5 (CMIP5) coordinated by IPCC provide a GCM data base for scientific interpretations [IPCC, 2013]. These data are made available to general scientific community by IPCC Data Distribution Centre (http://www.ipccddc.cru.uea.ac.uk/).

APPLICATIONS OF GCMS IN CLIMATE CHANGE STUDIES

GCMs have been widely used in climate change studies and their applications can vary from simulation and modelling of climate variables to prediction of stream flow and estimation of crop yields. For examples, the study conducted by Kripalani *et al* [2007a] over East Asian region based on IPCC AR4 (CMIP 3) models predicted significant change in mean annual precipitation. However, changes in mean precipitation varies from model to model (–0.6% for CNRM-CM3 and 14% for ECHO-G and HadCM3) respectively. In another study undertaken over South Asia, a rise of 8% in mean monsoon precipitation was reported under doubling of CO_2 scenario [Kripalani *et al.*, 2007b]. Based on the result derived from 5 GCMs, Sarthi *et al* [2012] observed rise in mean annual temperature (in the range of 0.6 °C to 1.8 °C) over the Himalayan and Tibetan region for the future period. Kumar *et al* [2013] have used 22 GCMs and three Regional Climate Models (RCMs) for predicting future patterns of temperature and precipitation under A1B emission scenario over India. This study based on ensembles of 22 GCMs (GCM_{EM}) as well as 3 RCMs (RCM_{EM}) indicates rise in annual surface temperature with respect to baseline period (1970–1999). The predicted increase in GCM_{EM}/RCM_{EM} for the periods 2010–2039, 2040–2069 and 2070–2099 with respect to baseline period is 1.1 °C/1.1 °C, 2.5 °C/2.2 °C and 3.9 °C/3.2 °C respectively. Similarly, rise in mean annual precipitation including monsoon season is also predicted by the end of 21st century. However considerable spatial variability is observed in pattern of precipitation.

Recently, the responses of East Asia summer precipitation to global warming have been studied by Qu *et al* [2014] using ensembles of 16 CMIP 5 models. The results derived from this study predicts increase in overall summer precipitation over East Asia. The study of Wei *et al* [2009] conducted over China using high resolution Providing Regional Climates for Impacts Studies (PRECIS) model under A2 and B2 emission scenarios has revealed rise in mean annual temperature (from 1.3 °C to 4.5 °C under A2 and from 1.5 °C to 3.4 °C under B2), precipitation (from 5% to 17% under A2 and from 4% to 9% under B2) and radiation (0.5% to 1.1% under A2 and 0.5% to 0.9% under B2) for the periods of 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100) respectively. A comprehensive study of future (21st century) temperature change for Northern Eurasia using different CMIP5 models has been done by Miao *et al* [2014]. This study predicts rise in surface air temperature with the rates of 1.03 °C/100 year, 3.11 °C/100 year and 7.14 °C/100 year under the RCP 2.6, RCP 4.5 and RCP 8.5 scenarios, respectively. The projected rate of increase in temperature has been found comparatively higher for high latitude regions than the regions of low latitudes. In addition, the spring season contributes most to the decadal warming occurring under the RCP 2.6 and RCP 4.5 scenarios, while the winter season contributes most to the decadal warming occurring under the RCP 8.5 scenario.

In this line of research, Urrutia and Vuille [2009] have presented climate change projections (for temperature and precipitation) for the tropical Andes (mountainous region) using a RCM. The results derived from GCMs have shown significant changes in the frequency and magnitude of weather and climate extremes in future. There is high confidence that decrease in diurnal temperature range along with very cold days and increase in warm days coupled with increased rainfall intensity may occur in different parts of the Earth. Similar kinds of studies were also undertaken in other parts of the world; Europe by Ruosteenoja *et al* [2007], Africa by Diallo et al [2012] and South America by Solman [2013] respectively.

Further, the outputs of GCMs are readily applied in investigating consequences of future climate change on hydrology, glaciers, ecology, forestry, agriculture and water resource management studies respectively.

Limitations of GCMs

Despite notable development, GCMs still have some limitations as discussed below:

I. Most of GCMs considered in CMIP3 projects have included interactive land surface schemes *i.e.* fluxes from the land surface is felt by the modeled atmosphere. These schemes are quite sophisticated as they incorporate different vegetation types, interaction between solar radiation and canopy cover, transpiration, effect of soil moisture *etc*. However, carbon-cycle feedbacks are not generally modeled and possible changes in vegetation cover are not presently taken in account in climate change simulations [Brown et al., 2008].

II. GCMs are quite good in simulating planetary scale features but fail to resolve local scale topographic and sub-grid-scale processes and dynamics such as clouds, Jet Stream, El Nino Southern Oscillation (ENSO) because of their coarse spatial resolution. The decrease in spatial accuracy of GCMs simulated climate variables occurs from continental to local scale. This restricts the direct applications of GCM's outputs in regional climate change impact studies.

III. Due to simplified approximation of radiant-energy transfer and sub-grid scale parameterizations (*e.g.* cloud formations and dissipation, cumulous convections and turbulence), the large scale climate variables such as wind, temperature, humidity and sea level pressure are modeled more accurately by GCMs than the smaller scale hydrological variables *i.e.* precipitation, evaporation, evapotranspiration, soil moisture and discharge [Solaiman, 2011].

IV. GCMs have been found more skillful in predicting means (average) of temperature and precipitation than any higher order of statistics *i.e.* variability. Besides, higher confidence is achieved in estimation of temperature than precipitation. Extreme events such as length of dry spell, wet spell length and frequency of heavy rainfall events are poorly simulated by models even though mean annual precipitation is reasonably well simulated.

V. Present day GCMs usually make long term prediction of climate change and lack in ability of predict near term climate change *i.e.* climate variables on decadal time scales [Brown *et al.,* 2008]. However, emphasis has been focused on changes in climate that might occur within the span of few decades than century-length periods.

DOWNSCALING

GCMs as discussed above have been found incapable for detailed assessment of land surface processes and climate change impacts at local to regional scales, especially in regions with heterogeneous land cover and diverse topography [Wilby *et al.*, 2004]. As a result techniques usually known as 'downscaling' have been invented for narrowing the gap between the scale of GCMs and required resolution for impact assessment [Wilby and Dawson, 2013]. In downscaling, Large Scale Atmospheric Variables (LSAVs) are applied to predict local meteorological conditions [Willby and Dawson, 2013]. Thus, increase in spatial resolution of GCM's output is achieved.

This is mainly on the availability of archived observational and GCM data as both are required to generate future climate scenarios [Willby and Dawson, 2007]. The capability of downscaling in providing additional details can inform site specific assessment and management of climate risk. Based on literature review, downscaling can be grouped into two broad categories; dynamical and statistical downscaling [Fowler et al., 2007].

Dynamical Downscaling

Dynamical Downscaling (DD) involves development and use of Limited Area Models (LAMs) or Regional Climate Models (RCMs) for generating high resolution (10–50 km) outputs based on atmospheric physics over a region using GCM fields as boundary conditions [Giorgi and Mearns, 1999]. The extraction of local-scale information from large-scale GCM data is achieved by adopting following approaches; (I) running a regional scale LAM with coarse GCM data as geographical or spectral boundary conditions, (II) performing global-scale experiments with high resolution Atmosphere-GCM (AGCM), with coarse GCM data as initial (as partially and boundary) conditions and (III) the use of a variable-resolution global model with the highest resolution over the area of interest [Solaiman, 2011].

RCMs are more or less similar to GCMs in principles. They are nested within GCMs. This is performed to save processing time and costs in lieu of running the two models in successive fashion. Initial and boundary conditions required in calibration of RCMs are generated from the GCM or historical data base (NCEP/NCAR) [Brown *et al.*, 2008]. The individual choice of domain size controls the divergence between the RCMs and their driving GCMs [Jones *et al.*, 1997]. However, additional detail is also provided concerning the land use, coast lines, topographical structures and better resolved spatial gradients in physical fields [Kumar *et al.*, 2013]. It can bring significant change in regional flow patterns and increase the importance of local feedback processes such as snow-albedo/air temperature or soil moisture/air temperature feedbacks.

RCMs present a better description of topographic phenomena such as orographic effects and meso-scale circulation pattern than GCMs due to their high spatial resolution and ability of simulating finer dynamical processes. But in terms of temporal resolution, they have been found more skillful at monthly or coarser time scales than daily. The major drawbacks of RCM are its complex design and computationally expensive nature [Hewitson and Crane 1996].

However, there are certain issues which are still unresolved and are also plaguing RCMs [Brown *et al.*, 2008]. These include:

I. Parameterization of convective precipitation, mainly over tropics where convection is major source of moisture transport.

II. RCMs inherited biases systematically transmitted by GCMs in simulation of precipitation including extreme events. Therefore, use of model ensembles is to be recommended for a realistic assessment of climate change.

III. Based on large scale conditions defined by the host GCMs, RCMs assume fixed lateral fluxes into and out of their domain. Further, it is believed that evolution of climate within the RCM does not affect the output provided by the GCM. However, it is not true in reality.

IV. Because of computationally expensive nature, model integrations have, until recently, been restricted to 'time slices'; normally ~30 years for a control or 'baseline' climate from 1961–1990 and for a changed climate from 2070–2100 (Fowler et al. 2007). Scenarios for other periods are generated using 'pattern scaling' where changes are scaled according to the temperature signal modeled for the intervening period, assuming a linear pattern of change.

Statistical Downscaling

Statistical Downscaling (SD) technique is supported by the view; the regional climate is conditioned by large scale climate state and regional/local physiographic features

Table 1. Comparison of Main Statistical Downscaling Approaches [Wilby and Dawson, 2007]

Name of Method	Strength	Weakness
Weather Typing (*e.g.*, analogue method, hybrid approaches, fuzzy classification, self organizing maps, Monte Carlo methods)	• Yields physically interpretable linkages to surface climate • Versatile (e.g., can be applied to surface climate, air quality, flooding, erosion, etc.) • Compositing for analysis of extreme events	• Requires additional task of weather classification • Circulation-based schemes can be insensitive to future climate forcing • May not capture intra-type variations in surface climate
Weather Generator (*e.g.*, Markov chains, stochastic models, spell length methods, storm arrival times, mixture modelling)	• Production of large ensembles for uncertainty analysis or long simulations for extremes • Spatial interpolation of model parameters using landscape • Can generate sub-daily information	• Arbitrary adjustment of parameters for future climate • Unanticipated effects to secondary variables of changing precipitation parameters
Regression Method (*e.g.*, linear regression, neural networks, canonical correlation analysis, kriging)	• Relatively straightforward to apply • Employs full range of available predictor variables • "Off-the-shelf" solutions and software available	• Poor representation of observed variance • May assume linearity and/ or normality of data • Poor representation of extreme events

(*e.g.* topography, land-sea distribution and land use/land cover). In this technique, large scale atmospheric variables (predictors) of GCMs such as mean sea level pressure and geopotential heights are related to station-scale climate variables (predictands) such as temperature and precipitation based on statistical/empirical relationship [Raje and Mujumdar, 2011]. Based on these statistical/empirical relationships, local scale predictands (*e.g.* temperature and precipitation) can be downscaled at specific site or station. SD has shown advantage over DD approach as it is faster and simpler in use, less computationally expensive, provide site specific information and applicable for uncertainty and risk analyses [Yarnal *et al.,* 2001]. The requirement of long time series of historical weather stations data is a serious drawback of this approach.

Further, SD methodologies have been grouped into three sub-categories; weather typing, weather generator and regression/ transform function [Ghosh and Mujumdar, 2007]. The strength and weakness of each approach (shown in Table 1) has been reviewed in detail by Hewitson and Crane [1996] and Wilby and Dawson [2007].

Weather Typing establishes a sensible link between climate on large scale and weather at local scale [Wilby and Dawson, 2007]. It involves grouping of days into a finite number of discrete weather types or 'states' according to their synoptic similarity whereas weather states are defined either by applying cluster analysis to atmospheric field or using subjective circulation classification schemes [Wilby *et al.,* 2004]. The generated weather patterns are grouped into weather classes according to their similarity with nearest neighbours or a reference sets. It assumes that characteristics of weather class remain unchanged [Fowler et al., 2007].

The construction of future regional climate scenarios includes resampling of observed variables distribution or synthetically generated data (from Monte Carlo techniques) conditioned on daily weather patterns and associated with a given atmospheric circulation pattern produced by a GCM. The mean or frequency distribution of the local climate is then derived by weighting the local climate states with the relative frequencies of the weather classes simulated by GCM [Ghosh and Mujumdar, 2007].

This technique of downscaling provides multi-variables and multi-sites information [Wilby *et al.,* 2004]. However, it has shown limited success in downscaling 'rare' events (*e.g.* wet and dry spells) and precipitation changes produced by changes in the frequency of weather patterns are seldom consistent with the changes produced by host GCM [Wilby and Dawson, 2007]. This may be attributed to the relationship established between stationary circulation and surface climate. The methods based on this approach are; analogue method, hybrid approaches, fuzzy classification, self organizing maps and Monte Carlo methods respectively.

Weather Generators are stochastic models where climatic variables are conditioned by specific climatic events *i.e.* precipitation occurrence instead of weather pattern [Fowler *et al.,* 2007]. The daily climate is defined by outcomes on previous days. This involves two-state, first order Markow chains for simulating precipitation occurrence, gamma distribution predicting amount of precipitation on wet days and first-order trivariate autoregression conditioned by precipitation occurrence for simulating temperature and radiation components [Wilby and Dawson, 2007].

Recently, this has been found that weather typing scheme may also be used to drive weather generator models [Fowler *et al.,* 2007]. The study of Corte-Real *et al* [1999] used daily weather patterns derived from principal components of mean sea level pressure to condition a weather generator model. Further, advancement in modelling of the autocorrelation structure of wet and dry days is observed where the probability of rain is conditioned by the current circulation pattern and the weather regime of the previous day. This has been found skillful in simulating fundamental characteristics of precipitation including distribution of wet and dry spell lengths. The major drawback of this approach is that this is defined by local climate relationships and so may not be automatically applicable in other climates. Besides, inter-annual variability is also not accurately represented and they are underestimated.

Regression/Transform Functions are one of the most popular and widely used approaches applied in downscaling of large scale climate variables simulated by GCMs. In this approach, a linear or non-linear link is developed between predictors and predictands of interest and focus on changes in the central tendency of predictands [Schoof *et al.,* 2007]. There are different kinds of regression methods (based on choice of mathematical transfer functions, predictor variables and statistical fitting procedures) in practice which differ in complexity from simple multiple regression models to artificial neural networks, canonical correlation analysis and principal component analysis.

The methods based on this approach assume validity of the model parameters under future climate conditions similar with the weather typing methods. The choice of predictors and statistical forms affect the results of downscaling to the large extent. The major disadvantage of this approach is that it often explain only a fraction of the observed climate variability (especially in precipitation series) [Wilby and Dawson, 2007]. In spite of these limitations, the relative ease of application along with their use of observable trans–scale relationships have encouraged applications of these methods in downscaling of climate variables and performing impact assessment studies.

As discussed above, none of the approach (statistical downscaling approaches) has been found 'perfect' in downscaling and simulating climate variables for future periods. Therefore, attempts have been made to develop new approaches by combining one model with another. This may improve the simulation of variability as well as extremes. This has been confirmed by the study Kilsby *et al* [2007]. They observed that incorporation of a stochastic rainfall model into a weather generator has improved the simulation of both variability and extremes when compared to a simple Markov chain model. In this line of research Wilby *et al* [2002] have developed a hybrid model popularly known as 'Statistical Downscaling Model' abbreviated as SDSM. It is a combination of multiple regressions and stochastic weather generator based downscaling methods. It uses circulation patterns and moisture variables to condition local weather parameters and stochastic methods to inflate the variance of the downscaled climate series [Fowler *et al.,* 2007].

CONCLUSION

This review summarizes the progress achieved on Global climate modelling since the early efforts at the beginning of the 1960s until now. Results predicted by earlier GCMs inherited large uncertainties as they made simple approximation of physical processes and corrected it by flux adjustments. However, the newest generation of GCMs has eliminated the need for flux adjustment and relatively more realistic in their long-term prediction. The problems related to current capacity of GCMs such as failure in simulation of local scale topographic and sub-grid-scale processes and dynamics because of their low resolution have restricted their successful applications only to global and continental scales. The problem of discordant scales can be solved by using downscaling techniques. However, this may increase uncertainty in projection. Despite of these limitations, GCMs and their outputs have been found suitable in studying impacts of climate change hydrology, glaciers, ecology, forestry, agriculture and water resource management studies.

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Dharmaveer Singh is currently pursuing Ph.D. in the field of Geoinformatics in the Department of GIS Cell of Motilal Nehru National Institute of Technology, Allahabad, India. He has received his B.Sc. (Hons.) degree in 2007 and M.Sc. degree in 2009 in Geography (with specialization in Remote Sensing and Cartography) from Banaras Hindu University, Varanasi, India. He has four years of experience in field of research. He has published 08 papers in refereed journals and conference proceedings. His research interest includes hydro-climatology, hydrological modelling, water resource management and application of GIS and Remote Sensing in disaster management. He is life member of Indian Association of Hydrologist (IAH). He has been awarded Junior Research Fellowship in the field of Earth Science by Council of Scientific and Industrial Research (CSIR), India.

Sanjay K. Jain has received Ph.D. from Department of Earth Science, Indian Institute of Technology Roorkee, Roorkee, India in 2001 and M.S. in Hydrology from National University of Ireland, Galway, Ireland in 1997. He has more than twenty five years of experience in field of research. He is working as a scientist-F in Water Resources System division at National Institute of Hydrology, Roorkee, India and Officer-in-Charge of Indian National Committee on Climate Change (INCCC). He has 30 papers in refereed International Journals. He conducts research dealing with hydrological modeling, snow cover/ glacier mapping and snowmelt runoff modeling and impact of climate change on water resources. Dr. Jain is life member of Indian Association of Hydrologist, Indian Society of Remote Sensing, Indian Water Resources Society and International Association of Hydrological Society. He received best scientist award of National Institute of Hydrology for the year 2000.

R.D. Gupta is Professor in Department of Civil Engineering, Motilal Nehru National Institute of Technology, Allahabad (India) having specialization in Geoinformatics. Prof. Gupta obtained his B.E. (Civil) in 1985, M.E. (Remote Sensing & Photogrammetric Engineering) in 1990 and Ph.D. (Geoinformatics) in 2002, all from Indian Institute of Technology (IIT) Roorkee, India. He worked as Founding Coordinator for GIS Cell of the Institute and developed M. Tech. (GIS and Remote Sensing) course which was started under GIS Cell from the academic year 2006–07. He worked as Coordinator for signing of MoU between AIT Bangkok & MNNIT Allahabad in November 2010 to enable better academic interaction. He worked as one of the Investigators for ISPRS and ISRO Cartosat-1 Scientific Assessment Programme (C-SAP) for the evaluation of PAN Stereo data for Test Site of Catalonia, Spain along with Dr. Manfred Lehner of DLR, Germany. He is presently working as Chief Coordinator for AICTE sponsored National Coordinated Project (NCP) on "GIS for development of Web based Public Health Information Infrastructure & Management System". He has teaching and research experience of over 26 years. He visited several foreign countries for research paper presentation and academic interaction including Tampa (USA), Spain, Thailand, Atlanta (USA) and Suzhou (China). He has published 70 research papers in refereed journals and conference proceedings and has supervised Ph.D. and M. Tech thesis works in the field of Geoinformatics

Amir Mor-Mussery[1]*, Arie Budovsky[2]
[1] Department of Geography and Environmental Development, Ben Gurion University of the Negev, Beersheva, Israel. 841050. Tel: 972-050-221-31-4.
* **Corresponding author**, e-mail: amir.mussery@gmail.com
[2] Ben Gurion University of the Negev, Bee'r Sheva, Israel. 841050 e-mail: abudovsky@gmail.com

THE IMPACT OF ROCKY TOPOGRAPHY ON SHRUBLAND HERBACEOUS PRODUCTIVITY IN SEMI-ARID ENVIRONMENTS

ABSTRACT. One of the consequences of soil erosion in arid and semi-arid environments is the emergence of rocky shrublands. While their existence is well documented, gaps exist in our understanding of processes affecting the soil fertility inside them and in their surrounded environment which is crucial for their successive sustainably management. Our aims were as follows: (i) assessing the impact of various parameters (geographical, chemical and physical) on the herbaceous cover in shrublands located in arid rocky areas; (ii) assessing the impact of the rocky topography on the fertility parameters at the inter-patches and surrounded matrix areas. Geographically, the site of study is located in private family farm at Chiran area, northern Negev, Israel. It has semi – arid climate (precipitation 200 mm year-1) with hilly rocky topography. Ecologically the area is sustainably grazed shrubland characterized by patch-matrix patterns.For analyzing the impact of the above mentioned parameters we chose 24 patches belonging to different geographic groups: "Inside the rock", "Adjacent to rock", "Parallel to rock" and "Slopped"). From each patch we took soil and herbaceous biomass samples from predefined locations based on the geographical patterns of each group. Four methodologies were implemented for analysis as follows: (i) comparisons between the actual values; (ii) ranking the differences between the patches" sub-plots; (iii) correlating the soil parameters with the herbaceous biomass using regression analysis; (iv) spatial analysis of the different parameters based on kriging. The results demonstrate that the most influential parameter in the plots inside the patch were the Soil Organic Matter and clay content. The soil moisture in this study did not affect the area fertility. The rocky topography, together with the patch spatial patterns had high impact on the values of the examined parameters, even when compared to the surrounding matrix. Altogether, the presented results indicate that the patch fertility is affected by combination of different soil parameters and the geographic topography of a given patch. Additionally, reciprocal effects between the patches and their surrounding environment are also important determinants of fertility. The techniques and methodologies demonstrated here could be applied to other landscapes as well.

KEY WORDS: slopped patches, adjacent to rock patches, parallel to rock patches, shrublands in rocky arid areas, inter-patch fertility, patches-matrix correlations

INTRODUCTION

Wide parts of the arid and semi-arid environments are defined as shrublands with patchy pattern. It was estimated using satellite imaging that in western Africa these shrublands occupy 16.3% from the total land cover [Fuller& Ottke, 2002]. Some researchers even claim that the state of the above mentioned patches can affect the rehabilitation of arid lands [Aguiar and Sala 1999], and in such a manner may have a dramatic impacts on the area erodibility and water balance [Jones et al 2006] and as a result, the potential for constructing sustainable agriculture systems [Gliessman1998]. Not only the values of the patch parameters such as the patch size [Mor-Mussery et al 2013], patch floral cover [Ludwig et al 2005], and patch structure [Aguiar and Sela 1999] affect a given area and indicate its rehabilitation or degradation state, but the heterogeneity itself could be a good indicator of the patch quality. In support of this claim is the following quote of Ludwig and Tongway [2005] –"Heterogeneity is crucial to the functioning of arid and semi-arid lands and changes in the scale of heterogeneity can be used to study and understand the processes underlying desertification and rehabilitation". Thus, the various aspects of geographical heterogeneity including slope angle [Bennie et al 2008] and stoniness [Bautista et al 2007] affect the functional state of patches. Moreover, the reverse is also true as the patch parameters affect the pattern of the ecosystem [Ludwig et al 2005].

It is important to note that one of the less studied and characterized type of shrublands, mainly due to its high heterogeneity, is the one which found in rocky areas [Omernik and Griffith 2011]. The need to study and model the processes occurring in these areas was emphasized by Xiuqin et al [2011] who recently claimed that one of the effects of soil erosion due to desertification is the creation of rocky topography. Thus, it is important to stress that understanding of these processes will allow sustainable management of such areas. Yet the previous comparative studies assumed that there are no predominant differences inside the patches themselves [for example, Katra et al 2008]. Here, we examine the existence of differences between soil parameters and their impact on the herbaceous biomass in shrublands located on rocky topography.

TOOLS AND METHODS

Site of study

The site of study is located inside private family farm in Chiran area, Northern Negev at the edges of Arad valley (34°59'04"E, 31°19'34"N). The area and its surroundings were heavily grazed till 1992. Afterwards, several family farms were established and the grazing was reduced inside their boundaries [reviewed by Olsvig-Whittaker et al 2006]. These changes caused an increase in the areal fertility [Leu et al. 2014] and its heterogeneity [Ludwig and Tongway 2005]. The site of study is located on south aspect hill slope (elevation is between 450 and 500 m ASL, slope' angle is between 7 – 10°, measured using Magnetic Ploycast Protractor of Empire®*).

The soil is defined as "sandy–clay–loam" based on USDA definitions [USDA 1999]. About quarter of the area has a rocky topography, laid mainly, with orientation perpendicular to hill slope (North-South), from Brecciccetedcuerts, Meishasu formation, Lake Cretaceous origin (definition by Prof. Haim Binyamini, Ben Gurion Univ.), with sizes between 4 and 25 m^2. In the wet season (December – February) the day temperatures were 8.1 – 19.1°C, while the summer temperatures were 21 – 35.3°C (based on measurements between 2000 and 2010).Yearly precipitation amount at the site is between 150 and 200 mm (IMS®, Israel Meteorological Services). In 2012–2014 the precipitation amounts in the farm were recorded by Aviv Oren as follows: 24.10.2013 – 16 mm; 5.12.2013 – 4 mm; 8.12.2013 – 7 mm; 10–14.12.2013 – 119 mm; 30.12.2013 – 16 mm; 15.2.2014 – 5 mm; 8.3.2014 – 23 mm; 12 –15.3.2014 – 81 mm.

Ecologically the area is defined as shrubland (shrub patches occupying 30% from the area and surrounded by matrix, Leu et al 2014], which is maintained sustainably grazed based on Ludwig and Tongway

Fig. 1. Site of study. Photo by A. Mor-Mussery, March 2014

[2000] principles. The patches are occupied mainly by species belonging to shrubs, geophytes, perennials herbs groups as follows: *Thymelea hirsute* (Thymelaeacae*), *Asphodelus ramosus* (Alliaceae), *Echinops polyceras*, *Artemisia sieberi* and *Artemisia arborescens* (Asteraceae), *Anchus astrigosa* and *Echium angustifolium* (Boraginaceae), *Salvia lanigera* (Lamiaceae), *Ferula communis* and *Pituranthos tortuosus* (Apiaceae), *Noaea mucronata* (Chenopodiaceae), *Sarcopoterium spinosum* (Rosaceae) and *Astragalus caprinus* (Fabaceae).

The herbaceous flora in the patches included mainly the following species***: *Avena sterilis*, *Stipa capensis* (Poaceae), *Calendula arvensis*, *Centaurea hyalolepis*, *Chrysanthemum coronarium*, *Negev Chamomile*** (Asteraceae), *Carrichtera annua* and *Reboudia pinnata* (Brassicaceae), *Onobrychis crista-gall* (Fabaceae)

* *In brackets – the family name*

** *Definition in doubt*

*** *Based on the sampling date (additional species were observed later in the season)*

The definitions of perennials were done by Dr. Bert Boeken and those of annuals by Prof. Pua Bar (Kutiel), both from Ben Gurion University of the Negev, Israel.

Sampling was implemented in March 2014 and additionally at September 2014, for patch 10.

Note. The tools and software do not represent the authors' preferences.

Sampling scheme and lab analysis

For separating between the patchy and the matrix parts of the tested rocky shrubland we used the definitions described in Mor-Mussery et al [2014a]. From these patches we selected ellipsoid ones settled by perennials (those settled by nests were omitted, Mor-Mussery et al 2014a] located on hill slope and adjacent to rocks. Particular for this study the following groups were studied: "Inside rock" – Patches located in the middle of plain rock without soil strips connected to the un-rocky area; "Slopped" – Patches located on hill slope far from rocks; "Adjacent to rock" – Slopped patches with rock in their north or south edges; and

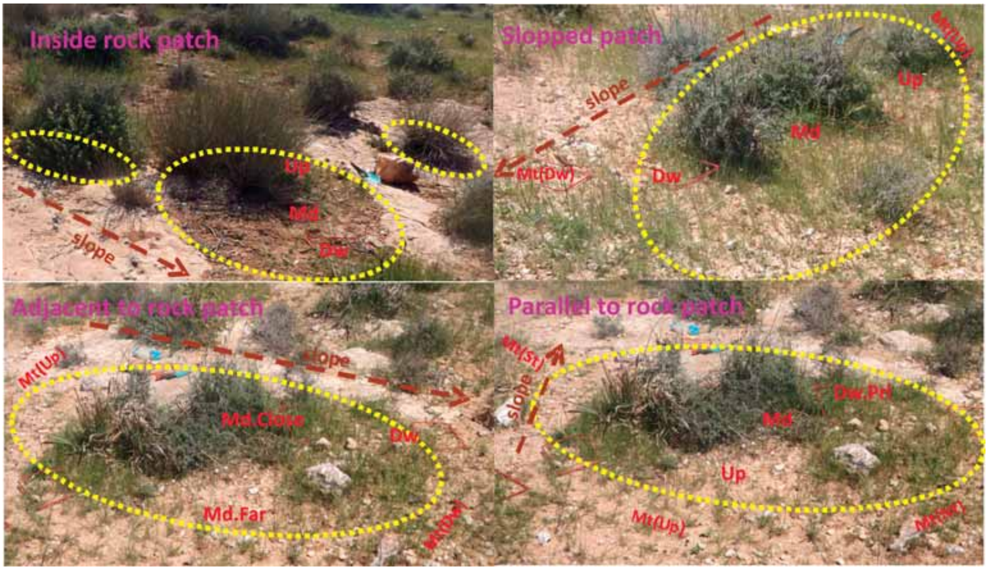

Fig. 2. Representative patches and their sub plots for the different studied groups. Photo by A. Mor-Mussery, March 2014

"Parallel to rock" – patches with rock on their lower part (their west edge).Total of 24 representative patches were chosen for the analysis, as follows: Ten for the "Inside rock", four for the "Sloped", four for the "Adjacent to rock" and six for the "Parallel to rock" group. Each patch was given a serial name.

Per each patch type a descriptive sub-patch sampling scheme was fitted, together with their adjacent matrix (the locations were chosen conceptually based on the water stream to patch – and out of it, [Aguiar and Sala, 1999]). The patches' sub-plots were abbreviate as "Pt" and the Matrix ones as "Mt". The subdivision was as follows:

For the "Inside rock" group, three parts were fitted*: patch upper part – "Pt(Up)", middle – "Pt(Md)" and lower – "Pt(Dw)".

For the "slopped" group five parts were defined: patch upper part – "Pt(Up)", middle – "Pt(Md)" and down – "Pt(Dw)", the adjacent upper matrix area – "Mt(Up)" and for the lower – "Mt(Dw)".

For the "adjacent to rock" group six parts were sampled: patch upper part – "Pt(Up)", the middle part which is close to rock – "Pt(Md. Cls)", the far one – "Pt(Md.Far)", lower – "Pt(Dw)", the adjacent upper matrix area – "Mt(Dw)" and the lower – "Mt(Up)".

For the "Parallel to rock" group six parts were defined: patch upper part – "Pt(Up)", middle – "Pt(Md)", the lower part which is adjacent to the rock – "Pt(Dw.Prl)", the adjacent upper matrix area – "Pt(Up)"*, for the upper matrix – "Mt(Up)", south – "Mt(St)", and for the north – "Mt(Nt)".

* *Due to research limitations, we excluded the analysis of the "Pt(Up)"*

For the fourth analysis we chose representative patch belonging to "Adjacent to rock" group (Numbered as "10") which was characterized by high spatial heterogeneity (topographically, closeness to rocks, settled shrubs, stoniness, etc.). In addition to the samples taken based on this group's predefined six parts, three (five in the second set) samples were taken all over the area in a random manner. The sample plots were documented relatively to the attribution point (marked as straight angle on adjacent rock) (Fig. 6, small frame).

From each patch part both soil and herbaceous biomass were taken randomly at 26.3.2014, and treated as described below. Herbaceous biomass was taken using 20X20cm iron frame, dried 48hours at 65^{o} and weighed (values in Kg m^{-2}). Soil samples were taken from soil surface till 15cm depth (root zone of annuals in arid areas, [Fischer and Turner 1978]). The soil samples were dried at 105°C to get rid of the soil moisture. Parts of the soil samples were burned at 400°C to determine the Soil Organic Matter(SOM) content based on protocols of Sava [1994]. The other parts of the soil samples were analyzed for mechanic content composition based on "Stocks law" and the protocols of Klute [1986], expressed in Silt and Clay percent from dry matter.

In order to assess the effect of stoniness on herbaceous cover inside patch Nr. "10",elevensoil samples of10X10cm size from surface till 15cm depth were taken at September 2014, dried at 105°C overnight and weighed. Afterwards, the soil was sieved using 11.4 mm and 0.36 mm diameter iron nets. This resulted in two fractions*: one of stones with Dm_{max}<11.4 mm and the other ofDm_{max}0.36-1.44 mm*. The stones fractions were weighed and expressed as percent from the total dry soil [Sheng 1990]. Afterwards the soil was mixed with 1Litter of water and the floated organic natter (roots, litter, etc.) was gathered, dried overnight, and weighed. The results were expressed as percent from the dry soil.

* *The filtering ability is based on the stone's maximal diameter [Sheng 1990].*

Data analysis

One of the biggest challenges of this work was choosing the most appropriate type of data analysis for detecting the differences between the patches groups' sub – parts in this rocky shrubland and identifying the soil parameters affecting the herbaceous biomass. For this purpose, we have constructed a four layer analyses system.

The first type of analysis was aimed at exploring the differences between the patches and their surrounding matrix. With this in mind, four parameters were defined and calculated as follows:

"Inter Patch Heterogeneity" – calculated by dividing the range between the maximal and minimal values by the minimal value. For example, patch Nr. 7 which contains the SOM values between 4.51 and 7.43 has the' Inter Patch Heterogeneity' value of ~51% (the calculation – 100*(7.43-4.51)/4.51). The values per each patch group were summarized and the resultant ranges were presented.

"Patch vs. Matrix" – was calculated by subtracting the averaged values of the patch sub-parts from those of their surrounding matrix. The results were calculated as percent from the patch average value. As example, for patch Nr. 20 with the averaged herbaceous biomass of 0.032 Kg m^{-2} and the surrounding matrix samples of0.08 Kg m^{-2} the calculated 'Patch vs. Matrix value was 82%. The results of all patches belonging to the studied group were documented and the ranges (extreme values) were presented.

"Patch vs. Matrix(Up)" – calculated by subtracting the upper matrix value from the averaged patch value. The results were presented relative to the patch average value. The "Patch vs. Matrix(Down)", "Patch vs. Matrix(North)" and "Patch vs. Matrix(South)" were calculated similarly with respect to the noted matrix. Negative results represent higher values in the matrix than those found in the patches (for example, for the silt concentration the difference in range between the patch and its surrounding matrix was: "$_{(-)}$78-33%", which means that in one extreme case the average value in the patch was 33% higher than that of the matrix, while at the other side of the range it was lower by 80%).For emphasizing and differentiating the negative values from those found in the range, they have been marked by lower-case brackets, as follows: "$_{(-)}$".

The second analysis was aimed at defining the heterogeneity inside the groups of different patches. The analysis is based on ranking the actual values according to their serial order of magnitude. For example, in Patch Nr. 11(belonging to "Adjacent to rock patches") the SOM values were as follows: "Pt(Up)" – 5.61, "Pt(Md.Cls)"-7.65, "Pt(Md. Far)"-6.19, "Pt(Dw)"-6.07, "Out(Dw)"-5.91 and "Out(Up)"-4.09%. Based on these values, the rankings were: "2", "6", "5", "4", "3" and "1", respectively. The ranks belonging to each patch part were averaged for each group and columns graphed. In such a way we illuminate differences between the patches due to the local geomorphological, ecological and other circumstances.

Note, in the case of patch belonging to the "Inside rock patches" group, the matrix value was calculated as the average of the whole matrix samples, due to the difficulty in defining the stream routes on the rock to the patch and out of it.

The third analysis which aimed at studying the relationship between the soil parameters and herbaceous biomass was done by intersecting their actual values based on linear trend line (separately for the inter-patches and the matrixes).

The integrative forth type of analysis was carried out in patch Nr. 10 by making spreading maps of the all above mentioned parameters (soil and herbaceous biomass ones) from the first set together with the stoniness, and soil litter parameters from the second one. The characteristics of the patch Nr. 10 were as follows: funnel shape, slope located, rock bordered from its north and south sides, area of ~8m^2, the slope angle range 18-26^o and in the west edge a strip width of 0.4m with 30^o angle settled with *Pituranthos tortuosus*, *Noaea mucronata* and *Asphodelus ramosus* in its edges (except the west side). The first set was based on nine sampling plots taken in spring (March, 2014) and 11 in the summer (August, 2014) (Fig. 6a).

These spreading values maps were visually compared to the herbaceous biomass cover one and the shrub locations as presented on the attached photo. The values spreading maps were prepared based on kriging analysis using GSWin® ver. 3.3[Gamma design 2013]. The definitions for the analyses were: semi-variogram based on spherical model, isotropic axis orientation, block kriging, and seven equal continuous categories [for further reading, Mor-Mussery et al 2014b; Turner 2005].

RESULTS

Even from the first sight it is clear that the differences inside the patches ("Inter-patch" parameter) with relation to all the examined factors, including SOM, are very high (even reaching above ten times difference). These results are noticeable mainly when they are compared to the differences observed between the surrounding matrix of the examined patches ("Patch-matrix(Sur)" parameter) which were found to be only several fold. Although high heterogeneity was present, several trends were observed. The lowest values were at the slopped patches group. The factors with the maximal differences were the herbaceous biomass, silt, and clay, while the most different groups were the "parallel to rock" and "adjacent to rock". Higher values in the matrix as compared to the patches belonged to the soil moisture, silt and clay factors.

The application of the more precise analysis (differentiating the matrix plot into the upper, lower parts, northern and southern sub-plots) showed that there were no differences between the north and south matrixes with relation to the patch average values of all the factors. The differences between the patches with regard to the herbaceous biomass, SOM and Silt were higher in case of the upper matrix when it was compared to the lower one (due to the sampling scheme, this comparison was done on patches belonging to the groups "Adjacent to rock" and "slopped"). The values were higher in the lower matrix with relation to the soil moisture factor. The clay values showed

Table 1. The differences in the soil and herbaceous biomass parameters between the inter-patches and their surrounding matrix

Parl. rock	Adj. rock	Slopped	Inside rock		
62–666%	132–1075%	125–199%	63–4,445%	**Inter-patch**	**Herbaceous Bm.**
66–94%	70–85%	33–90%	–	**Patch-matrix (Sur)**	
48–82 (St)%	57–90%	48–84%	–	**Patch-matrix (Dw)**	
54–99 (Nt)%	81–84%	(–)3–96%	–	**Patch-matrix (Up)**	
4–87%	15–42%	10–44%	20–405%	**Inter-patch**	**Moisture**
–78–29%	9–31%	(–)12–38%	–	**Patch-matrix (Sur)**	
(–)23–34 (St)%	18–42%	(–)23–85%	–	**Patch-matrix (Dw)**	
(–)133–34 (Nt)%	(–)1–57%	(–)9–27%	–	**Patch-matrix (Up)**	
11–101%	15–133%	13–51%	51–98%	**Inter-patch**	**SOM**
3–31%	14–26%	(–)10–20%	–	**Patch-matrix (Sur)**	
(–)8–30 (St)%	7–33%	(–)28–20%	–	**Patch-matrix (Dw)**	
(–)17–32 (Nt)%	14–36%	(–)13–22%	–	**Patch-matrix (Up)**	
35–1074%	117–173%	18–449%	68–195%	**Inter-patch**	**Silt**
(–)149–41%	(–)41– (–)5%	(–)78–33%	–	**Patch-matrix (Sur)**	
(–)168–81 (St)%	(–)26–53%	33–47%	–	**Patch-matrix (Dw)**	
(–)130–37 (Nt)%	(–)64–3%	(–)190–21%	–	**Patch-matrix (Up)**	
10–780%	92–165%	18–120%	74–733%	**Inter-patch**	**Clay**
(–)30–0%	(–)34%– (–)19	13–37%	–	**Patch-matrix (Sur)**	
(–)37–35%	(–)58–(–)26%	(–)2–47%	–	**Patch-matrix (Dw)**	
(–))68–(–)13%	(–)11–6%	20–50%	–	**Patch-matrix (Up)**	

Note "(–)" means higher value in the matrix compared to the patch
Table Abbreviations
"Inside rock" – Patches located inside rocks (the ones with two sampling plots)
"Slopped" – Patches located on hill slope far from rocks
"Adj. rock" – Patches located adjacent to rocks
"Parl. Rock" – Patches that their bottom is parallel to rock.
"Herbaceous Bm."– Herbaceous Biomass
"Patch-matrix (Sur)" – The patches averaged value vs. their surrounding matrix
"Patch-matrix (Up)" – The patches averaged value vs. their upper matrix, "Patch-matrix (Dw)" – vs. the down sampled matrix, ("Nt") – vs. the north sampled matrix and ("St") – vs. the south sampled matrix.
Note. The "Nt" and "St" abbreviation is referring only to the Parallel to rock patches group.

mixed trends. While in the “slopped patches” the higher differences were in the upper matrix, in the “Adjacent to rock patches” the higher differences were in the lower matrix.

The results in Table 1 clearly indicate that the higher differences between the patches, even the ones related to the same group, are due to local, undefined parameters affecting each patch in a different manner. In order to deal with this heterogeneity, we used the ranking analysis and widened it to the sub-patch plots (Fig 3).

The first analyzed factor is the soil moisture which is the most limiting factor in arid ecosystem. In general, the matrix has lower values than the patch plots. With regards to the sub-patches plots there was an increase in the soil moisturefrom the upper plots to the lower ones, with exception of the “slopped” group in which the lower parts were the

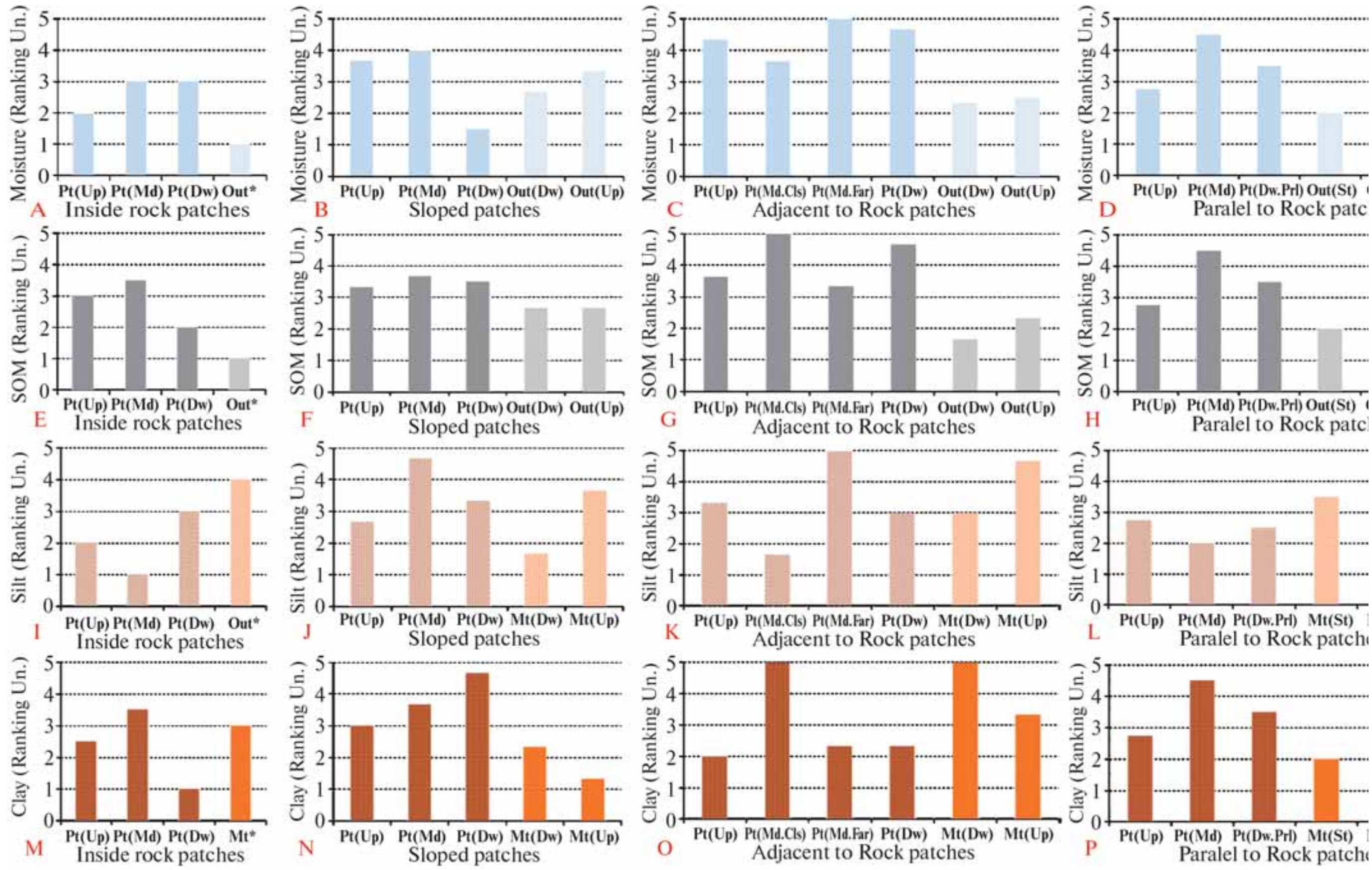

Fig. 3. Ranking values of the different soil parameters for the different patches groups.

A–D Moisture ranking values ("Inside rock", "Slopped", "Adjacent to rock", "Parallel to rock" groups, respectively). E–H SOM ranking values ("Inside rock", "Sloped", "Adjacent to rock", "Parallel to rock" groups, respectively). I–L Silt content ranking values ("Inside rock", "Sloped", "Adjacent to rock", "Parallel to rock" groups, respectively). M–P Clay content ranking values ("Inside rock", "Slopped", "Adjacent to rock", "Parallel to rock" groups, respectively).

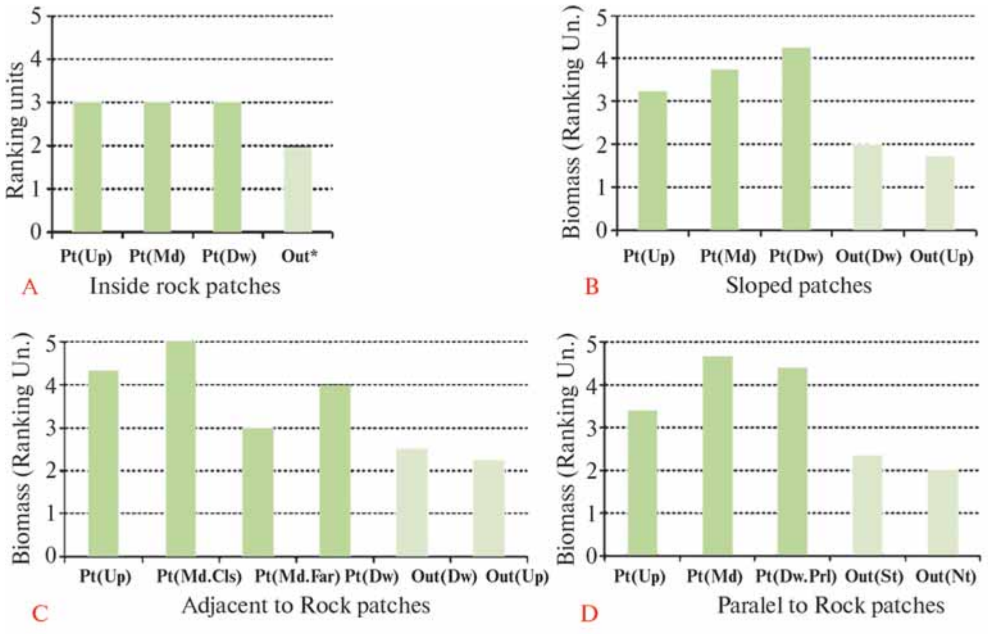

Fig. 4. Ranking values of the herbaceous biomass for the different patches groups.
A – "Inside rock", B – "Slopped", C – "Adjacent to rock" and "D – Parallel to rock" groups.

driest. Interestingly, the plots close to the rock ("Pt.Md.Close") did not have the highest values of soil moisture (Fig 3A-D).

The Soil Organic Matter (SOM) also demonstrated higher values in the lower plots of the examined patches. In the "Adjacent to rock" group the highest SOM values were at the lower part of the patch and adjacent to rock. Surprisingly, in the "parallel to rock" group the higher values were in the middle part (Fig. 3E-H).

As for the silt, the highest values were observed in the upper matrix sub-plots and in general decreased in the direction of the lower parts of patches. The higher silt values were observed in patches distanced from the rocks (Fig 3I-L).

Finally, the clay content increased in general in the descent direction in the sub-patch plots. However, in the "parallel to rock" group low values were found in the lower part of the patch parallel to the rock ("Pt(Dw.Prl)") (Fig 3M-P).

In the eyes of the land manager "the pivotal product" is the herbaceous biomass. Its values for the different sub-patches are summarized in Fig. 4. With regard to the herbaceous biomass in the "Inside rock" patches, there were no differences between the sub-patches plots. For the slopped patches there was a rise in the above mentioned value that paralleled the descent along the patch. In the "adjacent to rock patches" the higher values were located in the plots close to the rock, while the lower ones were found for the farthest from the rock plots (for the other plots no difference was observed). For the "parallel to rock" group the lowest value was at the upper part of the patch ("Pt(Up)"), and almost no difference was observed for the other parts.

After analyzing the inter-patch differences, we intersected the values of soil factors with those of the herbaceous biomass. The results are presented on Fig. 5.The soil moisture and the silt did not influence the herbaceous biomass both for the inter-patches and matrix sets, with higher deviation ("b" parameter of the linear trend line equation) observed for

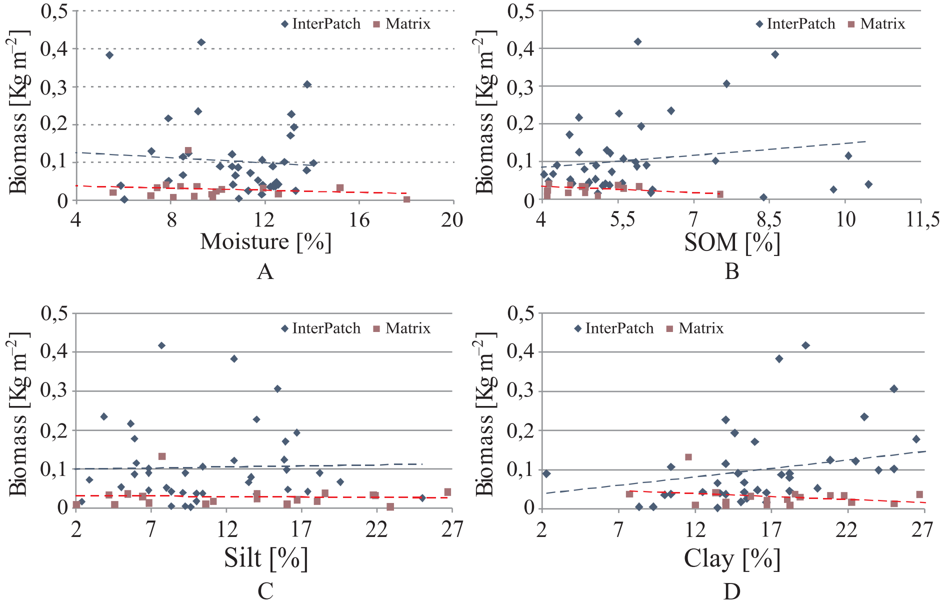

Fig. 5. The relationship between the soil parameters and the patch herbaceous biomass cover.

Rhombuses (blue) are representing the inter-patches plots and their trend line in dashed (blue). Rectangles (red) are representing the matrix plots and their trend line in dashed (red).

the inter-patch set.The SOM and clay factors had different effects on the inter-patches and the matrix plots. Whereas for the matrix plots the increase in the soil parameters did not affect the herbaceous biomass, for the patches plots the soil factors had a positive impact on it.

The first mapped parameter in patch Nr. 10 was the soil moisture. Its highest values were nearby the rocks and the biggest shrubs at the east and north edges of the plot, whereas the stream area had the lowest ones. According to the SOM map, the higher SOM values are found in small area around the sampling plots and then become blended and undetectable in the values category of the main stream. The clay map demonstrated accumulation inside the patch, whereas outside it and adjacent to the rocks the clay values were lower. The spreading map of 2nd stoniness ("Y" diameter between 0.36 and 1.44cm) demonstrated concentration in the lower part of the patch and in the upper matrix close to the patch.

The soil' litter (composed mainly of roots and humus, and to a lesser extent of flora slices due to grazing) was mainly spread near the *P. tortuosus* plants. Lesser quantity of the litter was found in the patch "body", and the lowest litter values were found in the downhill part of the patch. The herbaceous biomass values were high near the shrubs, but our analysis was not sensitive enough to detect changes in the biomass inside the patch "body".

In this work we investigated the abundance of several soil factors inside the given patches and their surrounding matrix located in slopped rocky areas. This was done in order to assess their effects on the herbaceous biomass of the examined areas. From the scientific documentation it is agreed that the most important factor effecting patch fertility in arid shrublands is the soil moisture (with regard to the term "arid" we also refer to the semi-arid areas). Although differences in the soil moisture values were found to be as expected according to Katra et al. [2008] (the higher values near the rocks, and lower ones down the patch), and paralleled the pattern of changes in the herbaceous biomass values, still these differences were not correlated in a statistically meaningful manner (Fig 5A). The

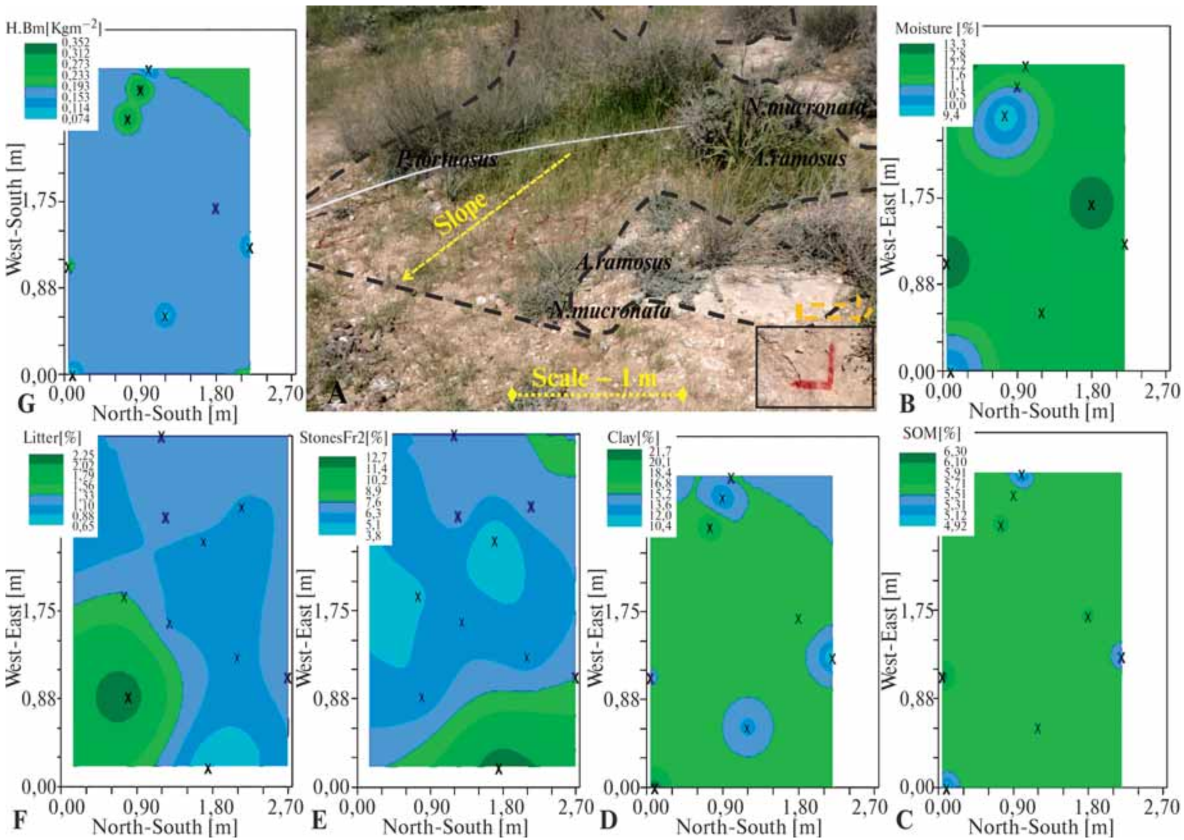

Fig. 6. The spreading maps (based on kriging analysis) of different parameters in patch Nr. 10.

A – The scaled photo of patch Nr. 10. (Photo by A. Mor-Mussery, March 2014).

**In small frame the red painted grids' start point on the adjacent rock . *Dashed grey represent the patch boundaries (the fertile area excluding the rocks)*

B – Spreading map of soil moisture (%), March 2014. C – Spreading map of Soil Organic Matter (%), March 2014. D – Spreading map of clay content (%), March 2014.

E – Spreading map of litter (%), August 2014. F – Spreading map of stoniness 1.4–0.36 cm (%), August 2014. G – Spreading map of herbaceous biomass (Kg m^{-2}), March 2014 lack of correlation in the case of annuals could be explained by the sensitivity of the annuals to the high moisture levels (as found in this study, and can be explained by the closeness of the last rain event to the time of the field study and its high intensity (12-15.3.2014 – 81 mm). This high moisture caused the soil to be over-saturated as demonstrated by lack of additional herbaceous growth during the sampling time [McMichael et al 2006]. Thus, later in the season, it would be expected that the soil moisture values will be more tightly correlated with the herbaceous biomass [Schwinning et al. 2004].

Our findings on annuals are in contrast to the tight and time independent correlations between the soil moisture and the shrubs' characteristics that were previously documented by Pariente [2002],indicating that shrub's characteristics are less affected by the sampling schedule than those belonging to the annuals.

From all the examined parameters the clay and SOM contents are the only ones that positively correlated (although not tightly) with the amount of the measured herbaceous biomass [Tongway and Ludwig 1996]; (Fig 5B& D). This could point to a possibility that combinations of the above mentioned and additional factors (soil, geographical, chemical etc.) should be examined in the future as candidates influencing the inter-patch fertility [Li et al 2008]. From the second set of measurements implemented on patch Nr. 10 (the soil stoniness and litter contents), negative correlation has been visually observed between the stoniness level of the second fraction, and the herbaceous biomass. However, further research is needed to attest these correlations.

The biggest challenge of this study was defining the differences between the inter-patch parts and transforming them into comparable values. For this purpose, four types of analyses based on work of Lloyd [2010] were specifically designed for this study. The first one (Table 1) is based on the comparisons of the actual values. Its biggest advantage is its reliability, but its main drawback is the high range of results. Thus, in table 1, we preferred to present the ranges and not the averages (could be misleading). The second type of analysis (presented in Fig. 3, relies on Hamby [1994] principles) is based on ranking the actual values of the examined factors. In such a way this methodology enables, on one side, to gather the combined values from patches located in different locations, and on the other side, to correlate the factor values to the inter-patches spatial differences. The third analysis is aimed at studying the interactions between the soil parameters and herbaceous biomass (Fig. 4), and is based on constructing regression that could be also used for studying the interplay between the above mentioned factors in patches' parts. Interestingly, we found that the examined factors affect differentially the herbaceous biomass in plots located inside the patch and in the matrix. This hints to a possibility of combined landscape effects.

As opposed to the former analyses that are based on ordinary statistics with fitness to spatial terms, the forth analysis performed by us belongs to the geo-statistics group. This type of analysis takes into concern not only the factor values, but also their locations in coordinates grid (we used the "kriging" type of analysis due to its relatively high frequent use in former ecological studies [Turner 2005]). The resulted spreading maps of the different factors in patch Nr. 10 demonstrated both the advantages and the drawbacks of kriging. Although the kriging analysis is based on "constrained" spatial analysis without taking into concern natural barriers or streaming paths such as rocks, it succeeded in drawing the actual boundaries of patch Nr. 10 based on the clay content values. This was also in agreement with the results of the former analyses. However, the "kriging" was less informative in the case of herbaceous biomass and SOM, which could be explained by the minor changes in their values in space [Bishop and McBratney2001]. With regard to the herbaceous biomass and SOM, these results were in controversy to those obtained by the former types of analyses which succeeded in identifying the differences between their values and the correlation between the factors. Overcoming of the above mentioned discrepancy could be achieved by visual comparisons between the spreading maps of the two sets (March and September 2014). Such a comparison demonstrated the wider distribution of values categories in the second set. The wider distribution could be explained by the higher number of samples (11 vs. 9), and the higher spatial distribution of the sampling locations as compared to the first set [Price et al 2000]. These factors (spreading and number of samples) should be taken into concern when choosing the sampling locations for the kriging analysis. An important advantage of the geo-statistics analyses is their ability to compare values that were taken in different locations and timing, such as the parameters that were taken in March and September in this study [Mor-Mussery et al. 2013a]. Of note, for this study we used visual examinations of the spreading maps, but statistical examination could be done by using the "Multi-layer" analysis [Mor-Mussery et al 2014b].

CONCLUSION

This paper is the first attempt to define and assess the relationships between different soil factors and herbaceous cover inside the patches (located in hilly and rocky topography) and with regard to their surrounding matrix. The dynamic and mixed effects of these parameters on the herbaceous biomass demonstrate the timing and the location importance, with regard to the measurements. For defining these dynamic interactions several analyses were used, part of which were unique to this study. Each of them highlights one aspect of these interactions, but only their integrative application (based on conventional, ranking and geo-statistics analyses) can advance our understanding about these processes and will allow in turn, better sustainable management of similar landscapes.

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The paper is dedicated to Dr. Bert Boeken ■

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Amir Mor-Mussery is the Agronomist, Soil, Environmental and Plant Scientist. He received his M.Sc. in Agricultural Genetic and Inheritance in 2003. Now he is the third degree student in Geography and Rural Development (Ben Gurion University). Since 2011 he is the agronomist and soil scientist (Wadi Attir project) and the Lecturer for Soil enhancement practices (2015). He is the author and co-author of numerous publications

Arie Budovsky is Researcher at the Judea Regional R&D Center (since 2010). He received his M.Sc. degree in 2004 and the PhD. in 2009 from the Faculty of Health Sciences, Ben-Gurion University of the Negev. His research interests are in the field of systems biology, medical applications of plants, network-based approaches, etc.

Cynthia Pizarro
National Council of Scientific and Technological Research and Buenos Aires University; Universidad de Buenos Aires, Facultad de Agronomía, Cátedra de Extensión y Sociología Rurales, Av. San Martín 4452, (1417) Buenos Aires, Argentina; Tel: +54 9 11 3525 8228; e-mail: cpizarro@agro.uba.ar, pizarro.cynthia@gmail.com

MIGRATION POLICIES AND STATE CONTROL IN ARGENTINA: EXPERIENCES OF VULNERABLE BOLIVIAN WOMEN WHO CROSS THE BORDERS

ABSTRACT. This paper analyzes the way in which migration policies impact in the trajectories of Bolivian women who live and work in the outskirts of the main cities of Argentina. It focuses on three cases representative of the experiences of women laborers who, coming from the poorest rural areas of Bolivia, crossed the international border when Argentine migration policy was very restrictive. It shows that symbolic and socio-economic borders keep on excluding them, as well as other labor migrants, within the Argentine territory even when the current Migration Law enacted in 2004 is more inclusive, since it grants human and social rights to the migrants. It highlights the way in which particular state control mechanisms operate nowadays both at the international border and within the Argentine territory, and analyses the difficulties that these women experience due to their positions of class, ethnic, gender, nationality and migratory status. It remarks that despite the changes in the immigration policy of Argentina, state policies keep on controlling labor migrations in accordance with the paradigm of the governance of migration. It also analyses the strategies that these women develop in order to sort out state control policies. Therefore, it considers that they are active agents even though they still have feelings of fear and trauma associated with the crossing of borders.

KEY WORDS: migration policies, state control, borders, women's labor migrations

INTRODUCTION

This paper analyzes the way in which migration policies impact in the trajectories of Bolivian women who live and work in the outskirts of the main cities of Argentina. It focuses on three cases representative of the experiences of women laborers who, coming from the poorest rural areas of Bolivia, crossed the international border when Argentine migration policy was very restrictive. In spite of the current more inclusive Migration Law enacted in 2004, symbolic and socio-economic borders keep on excluding within the Argentine territory and have a negative impact in the daily lives of these women.

We explore the way in which particular state control mechanisms operate both at the international border and within the Argentine territory. We show the difficulties that these women migrant laborers experience due to their positions of class, ethny, gender, nationality and migratory status. Despite the amends in the actual immigration policy of Argentina, which currently grants human and social rights to the immigrants, state policies keep on controlling labor migrations in accordance with the paradigm of the governance of migration.

We point out that there is still a feeling of fear and trauma associated with the crossing of borders. In addition, we refer to the agency of these women, analyzing the strategies they developed in order to sort out state control policies. The vivid experience of crossing an international border implies to identify oneself before the security forces of the country of origin as well as those of the host country (Sassone & Cortes, 2010). Thus, it is necessary to know the state policies, their requirements and due procedures. However, not everyone willing to cross the international border is updated with the issues required to entry a foreign country. Success not only depends on the kind of restrictions imposed by migration regulations, but also on the degree of arbitrariness of border controls and on the degree of socio-cultural vulnerability of potential immigrants (Pizarro, 2009a).

Socio-cultural vulnerability of labor immigrants occurs in both the country of origin and in the host country. It relates to the ways in which the intersection of different inequalities assigns them to specific social positions and to their various economic, social and cultural capitals. Both factors also affect, on one hand, their knowledge of how to cross borders and to move within a transnational social space (Tarrius, 2000) and, on the other, their degree of suffering.

Formally speaking, Argentina has an open immigration policy in favor of immigrants coming from the countries belonging to the Mercado Común del Sur (MERCOSUR, Common Market of the South)[1] as it is stated in the Ley de Migraciones de 2004 (Migration Law 2004). In addition, the national authorities launched a program that aimed to regularize the migratory status of the citizens of the MERCOSUR who had migrated before the enactment of that law (Pizarro, 2012a). Although the Argentine-Bolivian border is neither controlled nor militarized, as it is the case in other countries, this does not guarantee the inexistence of tensions and difficulties:

...There are regulations, rights, duties, fears, conflicts, prohibitions, fraud, abuses, uncertainty, strategies recorded in territories of walls without walls, at least in this region of South America (Sassone & Cortes, 2010: 227, our translation).

BOLIVIAN IMMIGRATION TO ARGENTINA

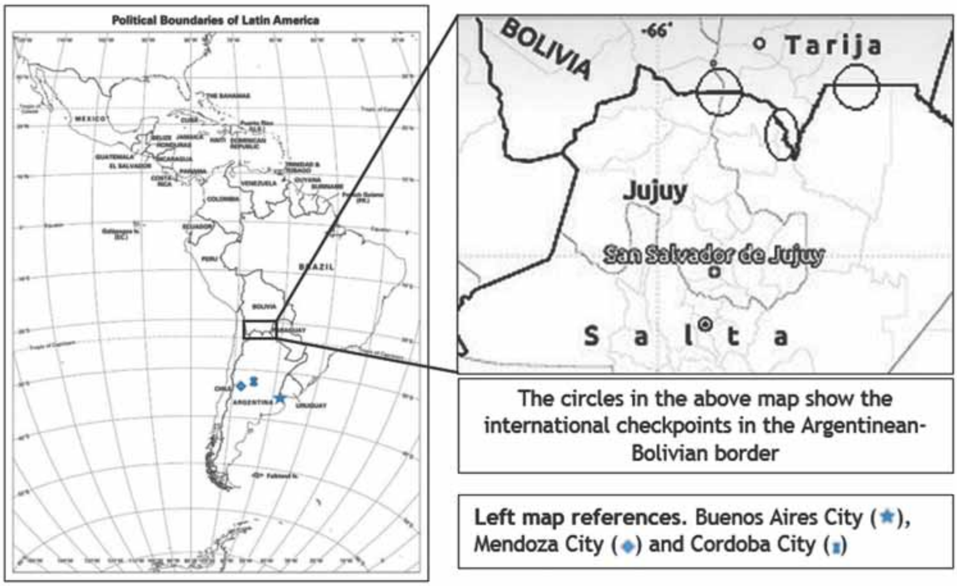
Latin American flows of immigrants to Argentina are long-standing since the first National Census of Population registered them in 1869. Besides, according to historical and archeological records, they have preceded the formation of the republican states. Until the mid-20th Century, these flows have coexisted with those coming from Europe and other countries of the world. Nevertheless, between 1880 and 1950 Argentine authorities only encouraged the latter, since they expected that Europeans would modernize the country and whiten the indigenous physical features and cultural manners of the native population.

Migration flows coming from neighboring countries[2] (see the map) have increased during the last 150 years in comparison with the decrease of transatlantic ones, which had been so important between 1869 and 1960 (see Fig. 1). According to Bologna (2010), European flows disappeared in the mid-20th Century because of economic and political reasons. The first relates to the changes in the economic situation of the sending countries, and the second to migration policies of Argentina.

On the contrary, as this author remarks, the entry of immigrants coming from neighboring countries has steadily continued. Nevertheless, they were only noticed when those immigrants coming from other continents (mainly from Europe and Asia) aged and there were no more new arrivals. As it can be seen in the results of the National Census of Population, the volumes of immigrants of both origins in 1991 were

[1] This group includes four member states: Brazil, Paraguay, Uruguay and Argentina and associated countries: Chile, Bolivia, Perú, Colombia, Venezuela and Ecuador.

[2] Chile, Bolivia, Paraguay, Brazil and Uruguay.



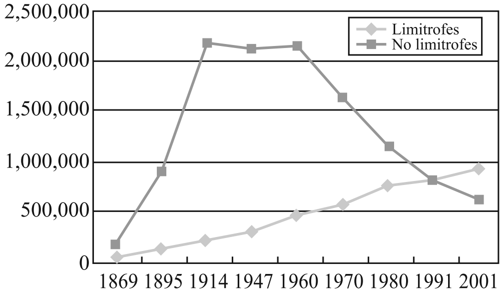


Fig. 1. Population born in neighboring (*limítrofes*) and non-neighboring (*no limítrofes*) countries between 1869 and 2001

equal, and in 2001, the amount of people born in neighboring countries (923,215) was 60,3% per cent of the total of foreigners (1,531,940).

The most important flows coming from neighboring countries to Argentina are the Paraguayan, the Bolivian and the Chilean ones. In 2001, the amount of people of those origins was more than half of the total of foreigners. Figure 2 shows the evolution of these flows between 1859 and 2001. According to Bologna (2010), only the Bolivian flow had a positive growth rate during the whole period.

In 2010, migrants coming from neighboring countries and Peru (which is also located in the South Cone of Latin America) were 77,6% of the foreign population in Argentina and 3,5 % of the total population (40,117,096), as Table 1 shows. The main migratory population groups were the Paraguayan in the first place and the Bolivian in the second. Bolivians were 0,85% of the total population (345,272).

According to Cerrutti and Parrado (2006), migration flows coming from neighboring countries and Peru increased during the 1990s because of the overvaluation of Argentine currency (Argentine Peso) in comparison with the American Dollar and

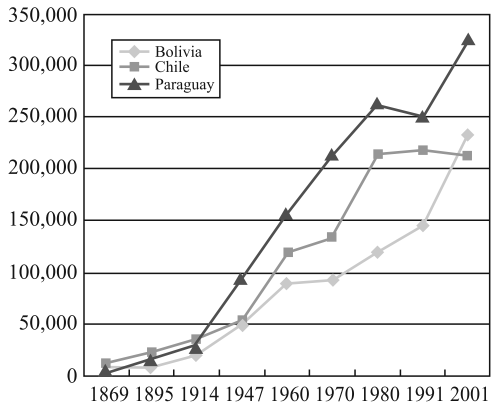


Fig. 2. Population born in neighboring countries between 1869 and 2001

Table 1. Evolution of the population of Argentina between 1980 and 2010

Year	Total population (1)	Foreign-born population (2)	(2)/(1) ratio	Neighboring countries-born population (3)	(3)/(1) ratio	(3)/(2) ratio
1980	27.947.446	1.903.159	6,8	753.428	2,7	39,5
1991	32.615.528	1.615.473	5,0	817.428	2,6	50,5
2001	36.260.130	1.531.904	4,2	923.215	2,6	60,2
2001(*)				1.009.800	2,8	65,9
2010	40.117.096	1.805.957	4,5	1.245.054	3,1	68,9
2010(*)				1.402.568	3,5	77,6

*Population born in neighboring countries and Peru
Source: Catillo & Gurrieri (2012: 19)

also due to the greater development of Argentine economy in relation to that of other Latin American countries. Benencia and Quaranta (2006) remark that intra-continental immigrants did not return to their homelands during the 2000s, even though there was a great economic crisis in Argentina in 2001 that caused a strong devaluation of the Argentine Peso and a high increase of unemployment.

In the case of Bolivian migration, it has steadily increased since the 1980s due to the economic and political situation in both Bolivia and Argentina (Domenech & Magliano, 2007) and because of the existence of long-standing migratory social networks. This flow is dynamic and is permanently renewing. It is a family migration since the amount of women and children has considerably increased since the 1960s.

Before 1950, male laborers migrated seasonally from Bolivian Andean rural households to the Argentine Provinces of Jujuy and Salta, located in the international border area (see the map below), in order to work in agriculture. After 1950, industrial modernization and urbanization processes in Argentina attracted Bolivian families southwards to the cities of Buenos Aires, Mendoza, and Cordoba. In the 1990s, a stable macroeconomic context, comparatively

Table 2. Spatial distribution in Argentine regions of migrants coming from neighboring countries and Peru, 2010

Region	Bolivia	Brazil	Chile	Paraguay	Uruguay	Peru
Buenos Aires City	22,1	25	5,1	14,5	26,3	38,4
Province of Buenos Aires	42,8	23,8	24,4	71,3	60,6	44
Outskirts of Buenos Aires	33,1	16,4	12,4	60,8	47,8	33,5
Other Areas of the Province of Buenos Aires	9,7	7,4	12	10,5	12,8	10,5
North West	16	2	1,4	0,3	0,9	1,5
North East	0,3	35,8	0,3	9,9	1,1	0,3
Cuyo	8,5	2,2	11,2	0,1	0,8	3,8
Patagonia	5,9	3,2	54,5	1,1	2,1	1,2
Center	4,2	7,7	2,8	2,4	7,9	10,6
TOTAL %	100	100	100	100	100	100
TOTAL	345.272	41.330	191.147	550.713	116.592	157.514

high salaries, and Bolivian potential immigrants' imaginaries about the Argentine modern and urbanized way of life made the country more attractive. Since then, Bolivians have spread all around Argentina (Benencia, 2012), taking jobs in low skilled and labor intensive sectors of the economy. As it can be seen in Table 2, in 2010, 65% of Bolivian immigrants lived in the city of Buenos Aires and its outskirts, 16% in the North West Region (international border area), and 8,5% in the Region of Cuyo (where the city of Mendoza is located).

International immigrants coming from impoverished social contexts usually integrate into marginal segmented labor markets (Herrera Lima, 2005; Portes, 1995; Pries, 1998; among others). In Argentina, there are specific informal sectors available for Bolivian labor immigrants such as construction, agriculture, small-scale industry, and domestic service (Bologna, 2010; Courtis & Pacecca, 2010; Pizarro, 2011). Labor informal agreements bring about a lack of access to social security and healthcare services as well as fewer possibilities of education for children and young people. Unlike natives, Bolivian workers usually accept to live and work under extremely poor conditions.

The concentration of Bolivians in urban areas has increased during the last 50 years possibly due to the availability of these kind of jobs (Table 3). According to the results

Table 3. Branches of economic activity that concentrate at least half of the Paraguayan, Bolivian and Chilean laborers residing in Argentina, according to sex, 2002

Male		Female	
Branch	**%**	**Branch**	**%**
Born in Paraguay			
Construction	31,4	Domestic Service	58
Manufacturing Industry	17	Trade	9,9
Trade	14,9	Manufacturing Industry	6,3
Other	36,7	Other	25,8
Total	100	Total	100
	62.275		58.829
Born in Bolivia			
Construction	26,6	Domestic Service[1]	26,9
Agriculture	23	Trade[2]	23,2
Manufacturing Industry[3]	19,4	Manufacturing Industry	13,6
Other	31	Other	36,3
Total	100	Total	100
	63.932		33.692
Born in Chile			
Construction	23,3	Domestic Service	35,3
Trade	15	Trade	15
Manufacturing Industry	14,2	Social Services and Health Care	8,5
Other	47,5	Other	41,2
Total	100	Total	100
	5.843		3.285

[1] Domestic services in private households
[2] Wholesalers and retailers; automobile service, motorbike service and other services
[3] Small-scale industry
Source: Bologna (2010: 183)

of the National Population Census 2002, Bolivian men mainly work in agriculture and women in domestic service. However, qualitative researches show that women and the whole families as well, work in the fields together with their male relatives in the outskirts of cities such as Buenos Aires, Córdoba and Mendoza (Benencia, 2008, 2009, 2012; Pizarro, 2009b, 2010, 2011; Pizarro & Trpin, 2012). One of the reasons of such subregister is that there is a common belief that work of women and children in this activity is just a help.

Bolivian labor immigrants are in the lowest positions of socio-economic and symbolic hierarchies both in Bolivia and in Argentina. Most of them were born rural peasant/indigenous areas, have low educational levels and are low skilled. In their homeland, they are discriminated with stereotypes such as "Peasants", "Indians", "Coyas" because of their indigenous phenotypes and certain cultural manners. Besides, they are expected to accept such unequal socio-cultural positions by being compliant, working in excess and not aiming to become rich or educated.

These previous experiences of oppression aggravate in Argentina, since these migrants are also placed in the lowest steps of the socio-cultural hierarchy (Pizarro, 2012a). They are radically defined as aliens because they have certain indigenous phenotypes and cultural manners that the hegemonic imagined white, modern and European-like Argentineness has systematically denied.

ARGENTINE MIGRATION LEGISLATION

Although during the second half of the 19th and the first half of the 20th Centuries Argentina promoted itself as a country opened up to international immigrants, it mainly expected the settlement of European citizens in order to whiten the physical features of native people and to modernize the country. When overseas immigrations declined in the 1950`s, the flows of migrants coming from bordering countries became evident. Since people coming from Latin America and Asia were considered "unwanted immigrants", several restrictions were imposed to them. For example, the Ley General de Migraciones y Fomento de la Inmigración N° 22439 of 1981 (Migration and Encouragement of Immigration Law 22439, 1981) brought about a closed and restrictive migration policy. In this way, the admission, entrance, permanent residence and exit of immigrants were highly controlled and those foreigners who did not have a regular migratory status became illegal and were obliged to exile[3].

In 1991, the MERCOSUR was created in accordance to a policy of regional integration that fostered the free movement of goods, capital and labor. It was thought that Argentina was experiencing "migratory problems" due to the steady territorial mobility of Paraguayans, Bolivians, Peruvians and other immigrants coming from the other countries of the block. At the same time, Argentine authorities endured additional international pressures due to the importance that the immigration issue had gained in the global agenda, and to the domestic activism of several nongovernmental organizations that claimed for the human rights of the immigrants. In this scenario, the Argentine State passed the Ley de Migraciones N° 25.827 (Migration Law 25.827) in January 2004.

This enactment brought about a change of direction in the immigration policy since it recognizes the right to migrate, and it fosters the equality of treatment of the immigrants and their access to information. It guarantees the non-discriminatory admission of citizens of the MERCOSUR and their access to social services, public benefits, health assistance, education, justice, work, employment and social security. It specifies that the irregular situation of a foreigner does not prevent him or her from being admitted as a student in educational institutions or from accessing to health, social or sanitary assistance.

[3] For a detailed analysis of Argentine Migration Legislation see: Courtis and Pacecca (2007); Domenech (2011); Novick (2008); Pizarro (2009a, 2012a); Sassone and Cortes (2010) among others.

It also says that the State of Argentina must develop measures aiming to regularize the migratory status of foreigners. In this way, some months after the Act was passed, the Programa Nacional de Normalización Documentaria Migratoria (National Program for the Regularization of Immigrants Identity Documents) called Patria Grande (Big Homeland) was launched for those foreigners born in the countries belonging to the MERCOSUR and the associate member countries.

Nevertheless, in spite of the change in the spirit of the Law that seeks for the inclusion of immigrants, the current policy is still framed by the paradigm of migration governance. This is so, among other factors, because state practices mainly aimed to the regularization of the administrative status of migrants (Domenech, 2011), and to the discrimination of different kinds of foreigners according to the type of permit of residence they are assigned and the activities they are allowed to perform (Courtis & Pacecca, 2007).

The Law establishes three categories of permits of residence: transitory, temporary and permanent. The transitory one is granted to all foreigners wishing to enter the country for a period of three months, but they are not allowed to work. In the case of citizens of the member states of MERCOSUR and associates, no visa is required.

In order to obtain the temporary residence permit for two years and to be allowed to work[4], it is necessary to go through many tricky bureaucratic proceedings that demand time, money and the know-how. No visa nor work permit is required for citizens of the member states of the MERCOSUR and associates. It is also necessary to go through uncomfortable proceedings in order to renew this permit after two years.

[4] This means that they have to register before the Agencia Fiscal de Ingresos Brutos (Tax Revenue Agency) and have to pay taxes when they start working.

After the period of two or four years of having a temporary residence permit, foreigners have to apply for a permanent one. This permit is granted to those who have Argentine relatives or can demonstrate that they have enough economic resources.

Entry to the country is allowed only through the international checkpoints authorized by the state. Those immigrants who enter through a clandestine route can be expelled from the country. It is also prohibited to offer jobs to irregular foreigners and to those having a transitory residence permit.

As we have seen, although many people think that current Argentine migration is open and receptive towards foreigners, there are too many legal requirements in addition to the expectation that applicants have the necessary economic, social and cultural capitals. Even though the amount of paperwork required in order to apply for the permits of residence is certainly less than the one under prior legislation, it is still a trap for many foreigners who are in the most vulnerable social positions such as labor migrants. This reveals a paradox: on the one hand, the Migration Law 2004 formally grants immigrants their human and social rights but, on the other hand, it creates several obstacles for their access to those rights (Pizarro, 2009a).

BORDERS AND STATE CONTROLS IN ARGENTINA

Changes in the law did not result in a decrease or optimization of border control procedures. Considering that borders are not only geographical but also administrative, legal, economic and symbolic (Grimson, 2000; Kearney, 2008), some foreigners keep on finding difficulties to cross them. Besides, borders have a great impact in their lives (Pizarro, 2009a).

According to Sassone and Cortes (2010), state immigration controls are carried out through mechanisms of inspection performed in the international border areas (checkpoints in international bridges, ports, airports and routes) as well as within the national territories. In the latter, controls can be performed both explicitly through public policies (source of employment, access to social services and police controls) or implicitly (bureaucratic obstacles, xenophobic mechanisms). Additionally, state officers and/or mediators construct the State in its margins[5] when they make or apply state regulations because, laws are universal but they have to be interpreted in each particular case (Asad, 2008), often leading to inaccuracies and arbitrariness (Fagundes Jardim, 2012).

In Argentina, there are three types of controls in international areas: security, customs and migration. Migratory controls are carried out in fixed checkpoints in bridges, airports and land routes by the Dirección General de Migraciones (General Direction of Migrations). Security controls are performed by the Policía Migratoria Auxiliar (Auxiliar Migration Police) and, in the case of those located in ports, by the Prefectura Naval (Naval Prefecture). Gendarmería Nacional (National Gendarmerie) is in charge of custom controls in fixed or movable checkpoints, which are located in nearby land routes.

Sassone and Cortes (2010) say that the five border checkpoints placed in the international border between Argentina and Bolivia (map) tend to be experienced as a distinguishing mark by the people who cross them since it is at that moment when they become immigrants and foreigners. Most Bolivians enter legally as tourists through these checkpoints with a transitory residence permit, but others cross by clandestine routes.

Although the border between Bolivia and Argentina cannot be compared to those militarized, such as the "Death border" between México and USA (Kovic & Kelly, 2006), migrants have always experienced abuse, discrimination, fear, terror, and/or anguish both before and after the Migration Law of 2004. The various control mechanisms are part of a state biopolitics (Foucault, 2009) and tend to be harder with Bolivians. This is because their phenotypes, ways of talking and corporal hexis recall Latin American indigenous ancestry, making them more vulnerable to arbitrariness and xenophobic discrimination (Pizarro, 2012a, 2012b).

THE EXPERIENCE OF CROSSING THE BORDERS OF VULNERABLE BOLIVIAN WOMEN

According to Sassone and Cortes (2010), crossing international borders can be a traumatic experience. However, it also challenges immigrants to create strategies in order to defeat control powers, which may vary according to their social positions both in their places of origin and in their migratory contexts[6].

The experience of crossing of the border will be less painful if potential immigrants know the formal and informal proceedings beforehand. According to the information that circulates among migratory social networks, they frequently know that they will find many obstacles such as to be asked for identity documents or arbitrarily delayed. They may also be aware that they might have to make several tries until they succeed.

During our fieldwork, we experienced one of the state control mechanisms that tended to prevent the entry of some Bolivian immigrants through a customs checkpoint located in the Province of Jujuy. A group of officers from the National Gendarmerie carried out the customs inspection with the explicit aim of controlling drug illegal trade:

One dark and cold night of August 2012, I was travelling by bus from La Quiaca (town

[5] These margins do not only refer to international borders but also to grey areas of state-society relationships within the social network (Das and Poole, 2008).

[6] Anthias (2006); Bastia (2013); Oso Casas (2008); Parella Rubio (2003); Rosas (2010), among others, have studied the way in which the intersection of class, race, gender and nationality inequalities influence the social positions, migratory and labor trajectories, and everyday experiences of migrant women, fostering or limiting their autonomy in different spheres of life.

located in the international border) to San Salvador de Jujuy (capital city of the Province of Jujuy) with three colleagues. The vehicle was stopped on a customs control checkpoint of the Prefecture. It was located on the route, roughly 50 km away from La Quiaca. All the passengers had to get off the bus with their luggage and to queue up at the edge of the route in front of a group of officers. One by one they had to open their bags and suitcases and the officers threw their contents to the floor in order to "look for drugs"[7] and "smuggled" goods. When their boss noticed that my colleagues and I were waiting in the queue for our turn, he invited us to go into the customs office since it was very cold. Our luggage was not checked and the officer apologized for the delay explaining that "bolitas" [8] always brought in "illegal" goods, referring in this way to drug trafficking and smuggled clothes that people usually buy in Bolivia and resell in Argentina. We thought that probably our clothes, skin color and corporal hexis made the officer think that we were not like the rest of the passengers and led him to treat us better (Fieldwork Diary, August 2012).

The groups that cross international borders in the most painful ways are usually young people without experience, women travelling alone, and migrants of rural or indigenous origins (Sassone & Cortes, 2010). As we suggested elsewhere (Pizarro, 2012a), people born in Bolivian peasant-indigenous areas are frequently oppressed and marginalized in their own country. In Argentina, their phenotypes and corporal hexis are associated with the indigenous ancestry denied by the hegemonic ideology of a white, European-like and modern nation. Besides, women from rural areas are discriminated because of their low level of education and lack of knowledge of Spanish. In short,

...the border becomes a place where thefts, aggressions and frauds are common ground. Some immigrants who lack of identity documents are able to cross them successfully when they turn to intermediaries in order to obtain a passport, residence permit papers or just to be assisted when crossing the border (Sassone and Cortes, 2010: 247, our translation).

The intersection of legal, administrative, economic and symbolic borders within the Argentine territory: to be torn between vulnerability, "ignorance" and "I don`t know why it happened to me"

Bolivian women who migrate to Argentina do not only feel their vulnerability at international border checkpoints but also within the national territory where symbolic and economic borders operate (Caggiano, 2007). Such is the case of Elena[9], who experienced a high level of suffering when trying to cross this kind of internal borders.

She was born in the Departamento de Potosí (Potosi District), located in the Andean Region of Bolivia, and is the daughter of peasants. She is a Quechua speaker and virtually illiterate. She travelled for the first time to Argentina in 1996 with her husband. At the beginning, they lived in Buenos Aires where she worked as a house cleaner until she got pregnant for the first time. After that, they moved to Mendoza where they worked in a brick factory and in a horticulture field.

Then, they went back to Bolivia, starting a coming and going period "as all peasants do". During this time, two more kids were born. Finally, they moved to the outskirts of the city of Cordoba where they worked in several brick factories. Around 2005, they took a piece of land and built a "tiny room" in an impoverished and peripheral neighborhood of the said city where they now live. Her husband works in construction and she knits clothing that sells informally in downtown streets. She sometimes complements the

[7] We use quotation marks to transcribe textual expressions recorded during our fieldwork.

[8] Discriminatory expression that is usually used in Argentina to refer to Bolivians.

[9] We use pseudonyms to preserve the identity of our interlocutors.

family incomes working seasonally in a potato field.

In 2009, we knew about the difficulties that Elena was encountering to cross the legal, administrative, socio-economic and symbolic borders between Bolivia and Argentina. We also became aware of the way in which state control mechanisms influenced her life and that of her family (Pérez, 2011; Pizarro, 2009a). At that time, it was critical for her to obtain the Argentine identity document. She had started the proceedings to regularize her migratory status four years ago with no success because she was accused of having a "false" Argentine ID, so the state officers withheld it.

She had obtained this "false" ID some years ago, when some officers from the Registro Nacional de las Personas [10] (National Register of People) had gone to the brick factory where she and her family used to live and work offering the possibility of quickly processing Argentine IDs for all the migrant laborers. Elena decided to apply for hers because she had lost her Bolivian ID and had not started any migratory process since then. She also applied for one for her eldest daughter who had never been registered as born in Argentina. This was so because Elena had been scared about being assisted at a hospital when she was born in 2001 since she was afraid of being "sent back to Bolivia" due to the illegal migratory status she had at that time (before the National Migration Law 2004). Therefore, Elena travelled to Bolivia with her family and registered the child as being born there. After that, they returned to Argentina.

Elena obtained both IDs. However, when she started the proceedings of the regularization program "Patria Grande" in 2004, she found out that those IDs were false[11]. Moreover, she was accused of giving false testimony because she had declared that her daughter was born in Argentina while at the same time the girl had been registered as a Bolivian citizen.

Therefore, neither she nor her daughter could regularize their migratory status although, in her opinion, she had done all the required proceedings. She remembered that the paperwork was too expensive and tedious, among other things, because she was told that she needed "two witnesses" that had to certify her address in order to "get the precarious". She knocked at the doors of several neighbors asking them for that favor, but nobody would do it for free, so she finally had to pay "$10 to each one".

Due to the irregularities found in both IDs, she had to go through different state offices. Besides, state officers usually said: "We cannot understand you and you do not understand us". Elena went to the Consulado de Bolivia (Consulate of Bolivia) where she was not assisted. She also asked for help to a migrant association called Centro de Residentes Bolivianos de Córdoba (Center of Bolivian Residents in Cordoba) whose president told her that he would charge $4000 to assist her in the process.

Elena was a victim of bad service and false information. There was certainly a problem of communication since Spanish is not her mother tongue, but above all, state officers and mediators lacked of a favorable predisposition to help her. They mistreated her either when she was alone or when she was accompanied by one of our research team members or by a lawyer of a nongovernmental association that gives legal assistance to vulnerable social sectors (Pérez, 2011). Nevertheless, Elena

[10] This state agency is responsible to issue the ID card in Argentina.

[11] The same state agency deceived eighty-four persons by issuing them false IDs. Therefore, they were not able to regularize their citizen status for many years. Mardones (quoted in Pizarro, 2009a) points out that the problem of false IDs is very common among immigrants in Argentina. According to this author, false IDs have different origins. Most of them were issued during the immigration amnesties of 1987 and 1992–94 while others correspond to a period of regular migratory proceedings. The degree of falseness of these IDs varies. It is significant that many of these documents were issued by a state agency that is in charge of extending national IDs. Still, illegal private mediators made others.

thought that she was treated worse when she was alone, since when she was accompanied the officers "don`t explain to me like that".

She was also very upset because the lack of IDs prevented her and her daughter to get access to social services even when, according to the Migration Law 2004, the state guarantees those services even to immigrants with no IDs or with an irregular migratory status. She explained that the officials in charge of a state program of social assistance aimed at families in risk of social vulnerability would not include her because "it is only for people who have IDs". She told us that, for the same reason, she was not allowed to be the legal guardian of her daughter and, therefore, she could not be awarded a scholarship. She also thought that she would not be able to register the girl at high school since at elementary school teachers demanded the girls' ID every year and she had to ask to the Head of the school to intervene.

Elena told us, while sobbing, that her husband blamed her for wanting to obtain the IDs and for "getting into that trouble", and that sometimes he hit her for that. In one occasion, she went to the police station to do a legal complaint but the police officer did not proceed because "I did not have the ID".

This case shows how state control mechanisms reinforce socio-economic, politic and cultural segregation among certain immigrants since the state itself creates illegality through actions and contradictions. This is an evidence of either the lack of instrumental rationality of state practices or its overuse (Pizarro, 2009a).

Elena asked us "what does counsel mean?", "What does precarious mean?" At the same time, she was not aware of the reasons why she had to go from one office to the other[12].

This shows that vulnerable migrants, as well as other impoverished citizens, suffer both objective and subjective legal marginality. The latter means that they perceive the legal system as being distant and unintelligible. Therefore, they do not consider it as a valid and/or effective way of resolving conflicts.

In 2009, Elena told us that she had endured all these difficulties because she was "ignorant". Some years later, when she had already obtained the IDs, she said that "maybe I haven`t understood them [the state officers], I don`t know, in the end I don`t know why it happened". According to Pérez (2014), immigrants with irregular status feel ashamed because they have low self-esteem and a tendency to blame themselves. This feeling is called potential statuary illegitimacy. Therefore, the substantive change introduced by Migration Law 2004 when it states that those foreigners, whose migratory status is not in order, are irregular but not illegal is blurred in everyday practices.

Elena suffered so much that she even dreamt about the IDs and the extremely difficult proceedings. Nevertheless, she had enough courage to go to the offices of the National Direction of Migration with a Peruvian friend who did not have an ID and had not regularized her migratory status yet because she did not have enough money and time. They were both upset because an urban bus company denied their children the student pass ticket, as it was also the case of other migrant children of their neighborhood and, for that reason, they could not attend school. Her friend, who had gone to the office "to speak on behalf of all", posed the problem to an officer, who questioned her about her migratory status. As her friend answered that she had not been able to proceed for the regularization, the officer said to her that if she had not have enough money, she should have spoken to a social assistant in order to be excused from payment. He said in a

[12] According to section 86 of the Migration Law 2004, "foreigners who are within the national territory and lack of economic means have the right to free legal advice concerning those administrative and judicial proceedings which can result in denying them permission to stay in the country, forcing them to return to their country of origin or expulsing them from the Argentine territory. Besides, they have the right to be assisted by an interpreter if they do not understand or speak the official language" (Pérez, 2014:18, our translation).

derogative tone: "How is it that you didn`t know that?" and added: "It is very easy to be in a status of illegality" (Pérez, 2011).

Finally, in 2013, Elena obtained both the residence permit and the ID. Her daughter also got her ID as it was proved that she had been born in Argentina. Therefore, she could finish her elementary education studies and started high school.

As Pérez (2014) remarks when she refers to the fetishism of papers, migrants usually highly value the opportunity to be granted residence permits and IDs since they imagine that they will have access to the same citizenship rights as nationals have. Elena`s obsession with getting those papers was due to her anxiety about fulfilling the necessary requirements to access the rights that immigrants are granted by law. The lack of information regarding the proceedings encourages the existence of children with no birth registration, and therefore, lacking of the correspondent ID. It is striking that the broadcasting made by Argentine state organizations, consulates, and non-governmental organizations is not accurate to improve the access of migrants to their rights. In addition, even though the proceedings are less tedious nowadays than they were before the Migration Law 2004, they are still too expensive, especially for impoverished labor immigrants.

The attitudes of Elena and her friend show that women tend to have a leading role in the running of migratory proceedings, and in the struggle to access to rights and social services for their children above all. In correspondence with the hegemonic gendered image of a good mother, they face a long path of bureaucratic rituals, controls and inspections, which are mechanisms of discipline that enact the biopolitics of the state (Fagundes Jardim, 2012).

As we have said before, controls are not located only in the international checkpoints. These mechanisms also operate in the bureaucratic proceedings that foreigners run in order to have access to rights such as residence permits, IDs, and social services. Such controls are reinforced when state officers and mediators mistreat those labor immigrants who are defined as "unwanted", as it is the case of vulnerable Bolivian women.

The intersection of geopolitical, administrative and legal borders: between "cutting the braids" or "getting lost"

Bolivians who wish to cross the international border and do not have the required documentation are frequently helped by relatives or acquaintances who have already done so. In other cases, they have access to the information that circulates through migratory social networks. As Sassone and Cortes (2010) say, it is necessary to know certain codes of conduct and strategies in order to become invisible when facing state officers. For example, regarding corporal hexis, it is important not to wear new clothes because of a possible suspicion of trafficking clothes. It is also recommended not to wear traditional clothes because they might be associated with those of indigenous peoples.

The case of Juana is an example of how to embody these strategies to cross the border, making profit of the know-how that circulates through migratory social networks. She was born in Tarija and she actually lives and works in a horticulture field in the outskirts of the city of Córdoba. She left Bolivia in 1998 when she was 19 years old:

We left our home because we felt very lonely. All of my dad`s family were in Mendoza and [all the relatives from her mum`s side], were born here [in Argentina], my grandparents, all of them were born in Buenos Aires. And they called us, 'What are you going to do there alone?' (...) The idea was mine really (...) I wanted to come and meet my family (...) and my father didn`t allow me, didn`t allow me. [He said:] 'You are living alone, what for?' I have two elder brothers and they didn`t agree with me coming here. 'I am going to work for a while and come back', I said, 'to be there, to meet our grandparents'. (...) I insisted. Then, my brothers said 'no, no, let`s go to Santa Cruz [city in Bolivia], if you don`t want to be in the countryside let`s go to the city', they told me (...) and we went to Santa Cruz (...) We stayed there for two years. From here, from Mendoza, an uncle went to visit us and said 'But what are you doing here? It`s nice over there'. The people over there, you know how they are, they say, 'in one year I bought me a van, I bought that'. We were thinking, we earn money [in Santa Cruz], yes [they worked harvesting sugar cane, and selling goods, clothes and food]. [The uncle told her father] 'How are you going to put your daughters to work like that, in the cane? My daughters over there don`t work'. Therefore, my eldest brother said 'I will see', he said, he went to Mendoza, to the field [where her relatives worked], with my uncle. He went there and said 'No, it's nice, so let`s go'.

Juana`s decision to leave was part of a family migratory project traversed by unequal gender and generation relationships. These inequalities overlapped with those related to her national ethnic origin when she crossed the international border with her family.

They crossed the highly controlled checkpoints without the required documentation. None of the members of her family had Bolivian documents because before "we weren't asked for them there in Bolivia, now they do [request them], but before they didn`t (...) there was not much control before". Their uncles went to pick them up to the border taking with them the IDs of their daughters and wives so that Juana and her relatives could pretend to be them. They also took "Argentine clothes" for Juana and her sisters and made them "cut their braids" to "look like" Argentine women. In this way, thanks to their uncles` help, they were able to cross the international checkpoints deceiving the controls of the state officers.

Once within the national territory the border raised again for Juana and her sisters. They worked with no Argentine IDs in Mendoza. Only her brothers and father had false ones. Juana wandered:

How is it possible that we had believed [that her father and brother's IDs] were good? One doesn`t know because over there [in Bolivia] it is different (...) We [the women of the family] also wanted to have our IDs and [her father and brothers] told us: 'No, you are women, what for?' and they acted like "machitos" [manly men], so they had their IDs done and such was the case that today they still have problems.

After some years, the women of the family ran the proceedings to obtain their residence permits and IDs according to the regulations of Migration Law 2004. Therefore, they were in a better position than her male relatives were. Nevertheless, this case shows that Bolivian women coming from the most impoverished social sectors are in a very vulnerable position. This is because gender and generation inequalities based on the patriarchal ideology of their homeland overlapped with those based on ethny and nationality in the migratory context.

The following case proves that some immigrants know how to cross the international border avoiding migratory controls. Raquel was also born in Tarija and she works at present in a horticulture field in the outskirts of Cordoba city. She went with her three children to Argentina in order to meet her brothers at the beginning of the 1990s. They crossed the international border through a clandestine route as if they were "lost", hidden among a big group of Bolivian immigrants.

The definition of herself and her sons as "lost" can be related to the category of vagrants. Tarrius (2000) suggests a typology to classify different kinds of mobility and territorial trajectories: diaspora, vagrancy and nomadism. Vagrants are migrants that do not keep bonds with their place of origin, go over many places throughout their trajectories, and keep a distance from the host society. Although this is not exactly the case of Raquel, we can identify some features of this category since, according to Tarrius' definition, vagrants are those migrants who are in an extremely vulnerable position, such as, "undocumented immigrants, exiled without support, fugitives, and people without material or symbolic resources due to unfortunate reasons" (Ibidem, 2000: 51, our translation).

After the current Argentine Migration Law was enacted in 2004, it was possible for Raquel to regularize her migratory status and that of her children so she ran the necessary proceedings and could obtain their IDs. However, in 2010, she told us that she was still scared about crossing the border back to Bolivia together with one of her sons because he was a minor, and she did not have the authorization of his father since she was a single mother. At the same time, her son was afraid because he thought that state officers would take away his computer during the controls.

Both Juana's and Raquel`s cases show that, even when vulnerable migrants might use certain strategies to successfully cross international borders no matter how restrictive policies may be, borders have a great impact in the trajectories and everyday lives of vulnerable labor migrants. Borders define who are welcome and who are not assigning foreigners the lowest social positions in particular migratory contexts. In Argentina, Bolivian immigrants coming from indigenous-peasant areas are highly discriminated and racialized. Xenophobic stereotypes and socio-economic vulnerability exacerbate in the case of women labor migrants coming from impoverished peasant-indigenous areas, highly constraining their possibility of achieving autonomy.

CONCLUSIONS

It is believed that Argentine migration policy is very inclusive, but this rhetoric of inclusion has limitations either in the letter of the current Migration Law and in state practices. Although this inclusive turn is desirable, it must not be taken for granted that this kind of migratory policy goes beyond the paradigm of migration governability that aims to control labor migrations.

There is a proclaimed intention to regularize the migratory status of foreigners, especially of the citizens of the MERCOSUR. However, the proceedings for obtaining residence permits and IDs, and the arbitrariness and xenophobic discrimination of state officers foster a considerable amount of "irregular immigrants". The impact of such label does not differ so much from that of "illegal migrants" in the prior legislation based on a rhetoric of exclusion.

Explicit and implicit state controls are carried out in administrative, economic, politic and symbolic borders both in international areas and within the national territory. They tend to prevent the entry of the most vulnerable immigrants and to produce irregular ones, contributing to the availability of very cheap workforce eager to accept extremely precarious jobs.

The classification of who are the citizens of a political community and who are not is part of the political economy of culture that defines who are worthy to belong to the nation. As Vertovec (2011) says, the conceptual triad identity-borders-systems is a key instrument to build the national imaginary. In this sense, in a context of economic, legal and cultural systems marked by differences, international borders reinforce the sense of national identity of the people living in each side:

This triad is legitimized and reproduced through a system of narratives, public rituals, representations and institutions, informal social relationships, written and unwritten regulations, expectations of politeness and public behavior (Ibidem: 146, our translation).

In this scenario, policies and state institutions that control international borders become guardians of the nation. Besides, the images about borders projected by politicians, laws and the mass media affect the way in which migrations and immigrants are perceived, reinforcing moral borders. Certain categories such as irregularity or illegality (De Genova, 2002) lead people to support consciously or unconsciously the hegemonic prototype of the social order.

According to Kearney (2008), border systems have a double function. They standardize unequal economic exchanges influencing in this way the social position of migrants, and producing their cultural exclusion. As we have seen, Bolivian women coming from vulnerable indigenous-peasant areas are affected in both ways when crossing the borders to Argentina. However, even under such restrictions, some are able to avoid state control mechanisms.

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Cynthia Pizarro, PhD in Anthropology, University of Buenos Aires, Argentina. Professor at the School of Agriculture of the University of Buenos Aires. Researcher at the National Council of Scientific and Technological Research (CONICET). Coordinator of the Network of Argentine Researchers on Contemporary International Migrations. She has published several refereed papers on international migrations, anthropology of work, rural social studies, ethnicity and identity processes. Her last edited books are "Ser Boliviano" en la Región Metropolitana de la Ciudad de Cordoba. Localización Socio-espacial, Mercado de Trabajo y Relaciones Interculturales ("Being a Bolivian" in the Metropolitan Region of Cordoba City. Socio-Spatial Location, Labor Market and Intercultural Relations), 2011; Migraciones Internacionales Contemporáneas: Estudios para el Debate (Current International Migrations: Studies for Debate), 2011.

Mehretie Belay[1*], Woldeamlak Bewket[2]
1 Department of Geography and Environmental Studies, Debre Markos University
PO Box 269, Debre Markos, Ethiopia
* **Corresponding author**, e-mail: belaymehrete@yahoo.com
2 Department of Geography and Environmental Studies, Addis Ababa University
PO Box 150372, Addis Ababa, Ethiopia; e-mail: wbewket@geog.aau.edu.et

ENHANCING RURAL LIVELIHOODS THROUGH SUSTAINABLE LAND AND WATER MANAGEMENT IN NORTHWEST ETHIOPIA

ABSTRACT. Rural livelihoods (RLs) in highland Ethiopia is critically threatened by increasing degradation of land and water resources (LWRs) and lack of sufficient livelihood assets. In response, farmers adapted diverse indigenous land and water management (LWM) technologies and livelihood strategies. This paper describes farmers' methods of soil erosion identification and the practices of managing LWRs to enhance RLs. It presents the results of studies focusing on assessment of soil erosion indicators, farmers' in-built sustainable land and water management practices (LWMPs) and RLs in Dangila *woreda* (district) in the northwestern highlands of Ethiopia. Data were gathered from May 2010 to October 2013 through participatory transect walks, field observation, formal and informal discussions with farmers, examination of office documents and from a survey of 201 rural households. Descriptive statistics and the livelihood strategy diversification index (LSDI) were used to analyze the data. Results indicated that farmers employ around 13 indicators to identify soil erosion on their farmlands. Over 79% of the farmers indicated the occurrence of soil erosion on their farm fields and some 59% reported the trend was increasing for twenty years, 1991–2011. More than 174 km soil-bunds and greater than 4 km stone-bunds were constructed on farmlands and on grazing fields through farmer participatory watershed development campaigns. Some 34 gullies were stabilized using check-dams and vegetative measures. Almost 72% of the households applied cattle manure on about of their 75 ha lands to improve soil fertility. A total of 44 diversion canals and 34 water committees were established to facilitate the irrigation practice of 33% rural households. Over 20% farmers obtained results ranging from moderate to excellent by combining manure with chemical fertilizers in the same field. Nevertheless, introduced methods such as improved seeds and fertilizers were commented for unaffordable prices and short-range services. Farmers utilized over eight livelihood strategies but the mixed crop-livestock farming was their main source of income. Sharecropping contracts were the ways of stabilizing the land demands of the studied households. It is concluded that integrated use of technologies (i.e. structural & vegetative plus indigenous & introduced measures) and participatory research & planning should be promoted to improve farmers' LWMPs and livelihoods. Increased effort should be made by concerned agencies to help farmers own assets (e.g. farm land) and diversify their livelihoods strategies. Special focus should be also given to farmers' inbuilt LWMPs and livelihood strategies.

KEY WORDS: Rural livelihoods; farmers' methods; sustainable land management; Ethiopia.

INTRODUCTION

The livelihood of rural people in the developing countries of sub-Saharan Africa (SSA) strongly relies on farming and exploitation of natural resources. But, farming in these countries is greatly confronted with resource degradation and unsustainable resource use. Resource degradation and pervasive poverty deprive the rural people in these countries from holding essential livelihood assets. The condition hampers the ability of farmers to produce food supplies; weakened their capacity to cope-up risks and exacerbate their vulnerability to shocks [Shiferaw *et al*., 2009]. It also diminishes the capacity of farmers to invest on sustainable natural resource management (SNRM) and uphold sustainable rural livelihoods (SRLs). The appalling impacts of land degradation in these countries are in general reflected through the loss of the inherent potential of LWRs in the form of soil fertility depletion and declining agricultural potential [Shiferaw *et al*., 2009; Schmidt and Tadesse, 2012]. For instance, in Ethiopia a total of 1,493 million tonnes of soil is lost annually at the rate of 12 t ha^{-1} yr^{-1} on average [EPA, 2012]. Around 17% of the agricultural gross domestic product (agricultural GDP) of the country is estimated to be lost each year due to physical and biological soil degradation [Amede *et al*. 2007]. According to Zeleke [2005], nearly 81 billion m^3 water hauling soil nutrients moves out of the country, and some 700,000 tonnes of grain crops are lost each year by burning dung.

Restoring and sustaining the natural resource base of agriculture has thus become imperative to SRLs in developing countries like Ethiopia. Understanding choices, needs and priorities of the rural households happens to be essential to design sustainable land and water management (SLWM) interventions [Shiferaw *et al*., 2009]. Hence, linking SNRM with SRLs has received significant focus in recent decades.

SLWM involves the activity of 'enhancing' and 'preserving' the productive potential of LWRs and grants enhanced options for continuous resource use and agricultural development. It is essentially linked to the application of soil and water conservation (SWC) technologies that match ecological, social and economic needs [Dumansky, 1997]. Livelihoods on the other hand refer to people and their resources, capacities and activities of making a living [Chambers and Conway, 1991]. The sustainability of making a living is determined by the presence or absence of assets. Livelihood assets enable rural people to own property [Barrett *et al*., 2001], enjoy meaningful life, and develop a sense of worth (respect and dignity) and to cope up with shocks and challenges [Nepali and Pyakuryal, 2011]. Farmers' access to basic assets such as farm land, water, forest, fodder and fuel are core indicators of SRLs and enable them to carryout SNRM practices. Diversity of choices, livelihood assets and strategies fix households' capabilities to cope-up with shocks and stresses, shape their investment and resource use efforts and to use new LWM technologies [Adato and Meinzen-Dick; 2002; Shiferaw *et al*., 2009]. But, LWRs can be easily exhausted if misused, disrupted and abused by improper practices. Hence, the sustainability of rural households can be threatened directly or indirectly [Chambers and Conway, 1991; Scoones, 1998] by their asset endowment levels. When farmers lack sufficient assets and institutions, they lose the base to invest on sustainable LWMPs [Shiferaw *et al*., 2009].

In Ethiopia, livelihood resources are endangered by the degradation of LWRs, population growth, rising social demands, and lack of equity and access and strong institutions [Anley *et al*., 2007]. The complex inter-linkages among poverty, population pressure, institutional failure and environmental degradation cause shrinkage of land holdings that led to farm fragmentation, landlessness and expansion of farming to steeper and marginal lands [Anley *et al*., 2007]. Due to increased population pressure and continual land degradation, the size of agricultural land (i.e. the basic livelihood asset) is continuously shortened [Teklu and Lemi, 2004]. Hence, farmers entirely abandoned the traditional practice of using natural fallow to restore soil fertility [Zeleke *et al.,* 2006]. Average per capita crop land for instance declined from 1.96 ha in 1957 to 0.53 ha in 2000 in the Baressa watershed, central highlands of Ethiopia [Amsalu, 2006]. Adenew and Abdi [2005] also note that the average landholding per household and per capita landholding in the Amhara Region measures only 1.1 and 0.24 ha, respectively.

Rural households continuously devise different livelihood strategies and SLWM methods in response to the aforementioned context factors [Shiferaw *et al*., 2009]. Vigiak *et al*. [2005] indicate that farmers have deeper perceptions on soil erosion than agricultural experts. These authors note that farmers' concepts of soil erosion indicators have closer linkages with scientific methods. Ethiopian farmers also use diverse indigenous LWM systems that have been exercised for centuries. Abera and Belachew [2011] indicate that farmers use their knowledge of soil color, texture and water holding capacity to classify soils in terms of fertility. Erkossa and Ayele [2003] note that farmers identify four soil types: black, red, *Koticha* and sandy soils using color and texture. These authors rank soils based on their area coverage, fertility and response to fertilizer. Tefera and Sterk [2010] also inform that farmers in the Fincha watershed shift livestock shelter from one farm to another to retain soil fertility using manure. Government sources indicate that Ethiopian farmers often implement indigenous and introduced SWC technologies. Such sources remark that the current agricultural system encourages application of both technologies to improve the livelihood of the rural people [EPA, 2012]. In recent decades, the farmers adapt external methods in response to the ongoing resource degradation and food deficiency problems.

Zeleke *et al.* [2006] and Amede, *et al*. [2007] indicated that farmer participatory planning and intervention managed by MERET[1] has been succeeding in degraded hillside restoration and income generation via homestead development projects in few sites of the country. Mekonnen and Tesfahunegn [2011] confirmed that participatory based SWC interventions started since the 1980s with the support of the food-for-work (FFW) program have been succeeding in improving the levels of soil depth, natural vegetation, surface and sub-surface water levels in Tigray, northern Ethiopia. EPA [2012] also noted that watersheds covering 1,958,000 ha approximate areas were covered with multipurpose trees; about 1,708,100 ha lands were treated with area closures; some 2,076,000 ha lands were treated with physical and biological SWC measures, and around 122,430 ha lands were irrigated between 2004/05 and 2009/10 through community participatory watershed development in different parts of Ethiopia. About 6.8 million ha degraded lands were stabilized through watershed based community participation campaigns in 2011/2012 [EPA, 2012]. Nevertheless, the ongoing farmer and government initiated NRM development is little researched and not accurately documented in academic literature.

This paper describes farmers' methods of soil erosion identification and the practices of managing LWRs to enhance rural livelihoods. The study was conducted in four rural *kebele* administrations (RKAs, lower levels of local government in rural Ethiopia) in the northwestern highlands of Ethiopia.

METHODS AND MATERIALS

The study area

The study was conducted in four RKAs named Abadira, Badani, Dubi and Gayta in Dangila *woreda* in the northwestern highlands of Ethiopia (Fig. 1). The total land size of the study RKAs measures about 114.90 km^2. They form part of the northwestern highlands of Ethiopia where their elevations vary from 1,800 m asl in the southern plains of Badani to over 2,300 m asl in Abadira and Gayta. The micro-relief

[1] Managing Environmental Resources to Enable Transition to more Sustainable Livelihoods.

in the study RKAs is broken by small streams and wider gullies that often fill with rainwater during *kiremt* (the rainy season). Around 46 streams flow in the area of which 74% are used for irrigation. Based on records at Dangila town, the mean annual temperature in the study areas is about 17 °C and the annual rainfall is 1578 mm. About 93% of the total rainfall occurs between May and October with peaks in June, July and August. These three months account for 62% of the total annual rainfall [see Belay and Bewket, 2013a, 2013b & 2013c].

Based on color, the local farmers identify four soil groups: red color (*Forefor*), black color (*Mezega*), grey-brown (*Bunama*) and dark brown (*Abolse*) as dominating the areas. The red soils (which belong to the Nitosols group) commonly occur on hilly and sloping parts in about half of the study areas. They have a clay-loam texture and are most intensively cultivated, but also most seriously eroded. The black soils (Vertisols group) are more prevalent in Abadira, Badani and Dubi and often cover low-lying landscapes. The grey-brown soils (Luvisols group) frequently occupy the pediments in all areas. The dark-brown (Cambisols group) mainly occur in forested and previously settled areas and village compounds of the study areas, but widely observed in the northwestern margins of Abadira. Croton (*Croton macrostachyus*), Vernonia (*Vernonia amygdalina*), Acacia (*Acacia lahai*), Eucalyptus (*Eucalyptus camaldulensis*), Cordia (*Cordia africana*), Albizia (*Albizia gummifera*), Terminalia (*Terminalia brownie*) and Justicia (*Justicia schimperiana*) form the dominant vegetation types [Belay and Bewket, 2013a, 2013b & 2013c].

About 22,883 people inhabited the four RKAs in 3,343 households. Crop-livestock mixed subsistence farming is the basic source of livelihood of the people. Maize (*Zea mays*) in Badani and Dubi and *tef* (*Eragrostis tef*) in Gayta and Abadira are the leading crops in area coverage and quantity of output. Finger millet (*Eleusine coracana*), potato (*Solanum tuberosum*), oil seeds and pulses are among the crops grown in the RKAs. Vegetables and fruits are important crops cultivated using traditional irrigation around the homesteads in Dubi and Gayta [Belay and Bewket, 2013a, 2013b & 2013c].

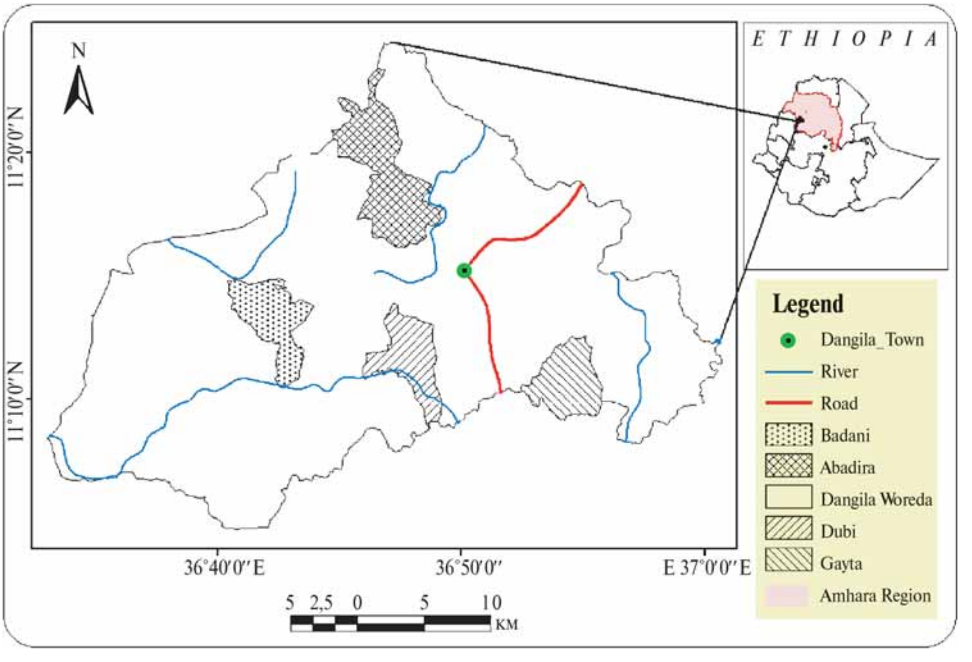

Fig. 1. Location map of the study area [Belay and Bewket, 2012a]

Data and Methods

The data used in this study were gathered from May 2010 to October 2013. The background data was gathered from unpublished reports and archives available at the study RKAs and the district agriculture office. Participatory transect walks, field observations, structured questionnaire surveys and formal and informal discussions were used to generate the primary data. During the survey, farmers' groups (FGs) were organized in the RKAs to work together with the lead researcher in field measurements, observations and transect walks. DAs working at RKA levels in natural resource, crop, livestock and irrigation development were involved in the discussions, transect walks and field observations. The primary data from FG discussions, field observation and transect walks were gathered from the four RKAs (Abadira, Badani, Dubi and Gayta). The structured questionnaire survey data were generated from 201 households selected using proportional systematic random sampling techniques from only three RKAs (Badani, Dubi and Gayta) for the purpose of another study and used in this paper. Data from published sources were also used to enrich the data gathered from different sources.

A livelihood strategy diversification index (LSDI) was computed to assess the degree of income diversity of livelihood activities. According to Wang *et al.* [2010], LSDI increases with increasing in the number of income generating activities and when the income share of the activities grow to be steadily normal; but decreases with a decrease in the number of activities and approaches zero when the coping strategy is one. Conversely, specialization increases with decreasing in the number of activities and when the income share of one or a few activities get larger than other activities. The LSDI for this study was thus computed using the formula used in Wang *et al.* [2010]: LSDI = 1 – H, where H is the Hirschman-Herfindahl index [kurosaki, 2003; Woerheide and Persson, 2008]:

$$H=\sum_{k=1}^{n} S_k^2;$$

$$LSDI=1-\sum_{k=1}^{n} S_K^2,$$

Where LSDI is livelihood strategy diversification index; S_k is the income share of the k activity in decimal units; k is the livelihood activity and n is the number of livelihood activities. The qualitative information obtained from formal and informal discussions was used to verify the quantitative information. The Statistical Package for Social Scientists (SPSS Version 15) and Microsoft Excel were used to manage and analyze the data.

RESULTS AND DISCUSSION

Land degradation identification and controlling practices by farmers

Like elsewhere in the world, farmers in northwest Ethiopia encounter problems of soil erosion. Over 79% of the farmers approached indicated the occurrence of soil erosion on their farm fields and some 59% reported the trend was increasing for twenty years 1991–2011 (Table 1). A field measurement study (Table 2) discovered the removal of some 82,692 tonnes of soil from 26 gullies and an average erosion rate of 16 t ha^{-1} yr^{-1} from 31 farms in two RKAs. Gully expansion has caused the loss of 4.66 ha cropped areas and an estimated ETB 2,631 crop yields. The severity of the erosion problem was rated moderate by 32%, severe by 24%, low by 20%, very low by 13% and very severe by 7% of the participant farmers (Table 1). Similar perceptions of considering soil erosion as severe and increasing trend were reported by the majority of the famers in the Digil watershed, northwestern Ethiopia [see Bewket, 2007].

During the questionnaire survey and in FG discussions, farmers were asked to specify what indicators they use to identify the prevalence of soil erosion on their farm fields and what methods they employ to manage

Table 1. Farmers' perceptions on soil erosion

Farmers' responses	% of reporters (n = 201)
Appearance of soil erosion on your farm plot	79.1
Trend of erosion on your farm in the past 20 years:	
increasing	58.7
no change	21.4
decreasing	16.4
no response	3.5
Severity of erosion on your farm in the past 20 years:	
very low	12.9
low	20.4
medium	32.3
severe	23.9
very severe	7
no response	3.5

Table 2. Soil erosion, land and crop damages and SWC measures in two RKAs (2010/2011)

Type of erosion damages & SWC measures	Size recorded for each
Erosion measured from tree root exposures (t ha^{-1} yr^{-1})	16
Erosion measured from gullies (tonnes)	82,692
Crop land damaged by gullies (ha)	4.66
Crop lost due to land damage (ETB)	2,631
Farms stabilized with soil terraces	32
Farms stabilized with stone-bunds	19
Farms stabilized with grass strips	39
Farms stabilized with ditches/water ways	52
Farms stabilized with cutoff drains	42
Gullies stabilized with catchment terraces	31
Gullies stabilized with check dams	19
Gullies stabilized with Sesbania	19
Gullies stabilized with Arundinaria	15
Gullies stabilized with Ipomoea	54
N° of farms assessed	31
N° of gullies assessed	26

Source: Adapted from Belay and Bewket [2012a & 2012b].

their land resources. Based on this, they mentioned various methods most of which are summarized in Tables 2. Checking the occurrence of water ways (gullies and rills), observing soil conditions (changes in soil colour and depth), looking the steepness of the land slope, evaluation of crop conditions (crop growth, seedling removal and yield changes), inspecting exposure of plant roots, and accumulation of sediments along lower farm margins were the major methods farmers use to check the occurrence of soil erosion on their farm fields. Most of these land degradation indicators conform to data reported in Vigiak *et al*. [2005] in Tanzania, Okoba and Sterk [2006] in Kenya and to methods used in Stocking and Murnaghan [2001].

Checking the occurrence of gullies and rills to identify the prevalence of soil erosion on farmlands was reported by about 63% and 41% of the farmers, respectively (Table 3). The use of gully to identify soil erosion by most farmers may be due to that gullies are easily and rapidly perceived than rills because of their large morphology and the direct damage of crops by gullies. Farmers continuously examine the occurrence of gullies and rills during their farming operations to check the prevalence of soil erosion on their farmlands. When they detect the appearance of these features, they perceive the occurrence of soil erosion on their farmlands and immediately take actions to reverse the problem. Constructing barriers from stones, soils, grasses and leaves across the channels or obliterating the waterways are among the immediate actions they apply. These structures are often performed during farming operations, very simple to apply and do not demand much labour and high cost. They are, therefore, implemented in a very short period of time and they are sustainable. For instance, check dams and catchment terraces were structures applied on the 19 and 31% of the assessed gullies, respectively. Plantation of sesbania (*Sesbania sesban*), Arundinaria *(Arundinaria donax*) and Ipomoea *(Ipomoea carnea)* were also measures adopted on 19, 15 and 54% of the assessed gullies, correspondingly (Table 2).

Observing soil conditions (depth and colour changes) is another method employed to check the presence of soil erosion on farm fields. Soil colour change is used by over 44% of the farmers. Sometimes farmers detect the prevalence of soil erosion when they get a hard rock while digging or ploughing their land. In this condition, they perceive that their soil depth is getting shallower because of the removal of the top soil by erosion and they concluded that there occurred severe erosion on their farmland. This method was also repeatedly used by about 63% of the participant farmers (Table 3). In such conditions, farmers often construct cutoff drains on the upper part of the farm to minimize further top soil removal.

Farmers can detect the prevalence of soil erosion by simply visualizing the land slope. If their land is located on a steep surface, they perceive the occurrence of soil erosion and prepare to take measures of protection. The usual performed measures include contour farming, cutoff drains, and construction of barriers such as stone and soil-bunds and grass strips (live-fences). During the field work, cutoff drains, soil terraces, grass strips and stone-bunds were observed on about of 42, 32, 39 and 19% of the farms surveyed, respectively (Table 2). Land slope was perceived as an indicator of soil erosion by about 67% of the farmers interviewed (Table 3).

When farmers observe more stone litters and exposed rocks and if it is strange for them, they suspect that the top soil has moved away by erosion and prepare to take actions to reverse the situation. Few farmers (18–22%) use this method. Tree root exposures are also most commonly used indicators by farmers as they are frequently occurring on farm fields. Inspecting the exposure of plant roots to identify soil erosion is used by about 43% of the farmers. Deposition of sediments on lower farm margins, along fences and stone barriers are also used by some 33% of the farmers to check the occurrence of soil erosion on farmlands and elsewhere in the environment. Fast moving muddy water is an indication of soil erosion for at least 26% of the total participants (Table 3).

Following-up the trend of crop growth, seed removal and yield changes, is another method

Table 3. Farmers' methods of land degradation identification

Method	Indicators		% of reporters (n = 201)
	Local name	English name	
Observing and checking:			
Occurrence of gullies	*Borebor*	Gully	62.7
Appearance of rills	*Boy*	Water way	40.8
The change in soil depth	*Yeafer tilket*	Soil depth	62.7
Soil colour change	*Yeafer kelem*	Soil color	44.8
Crop growth condition	*Sebil*	Crop	69.2
Crop seedling removal	*Yezer mekelat*	Seed removal	54.7
Reduction of crop yields	*Mirt*	Yield	73.6
Tree root exposure	*Yezaf sir*	Tree root	42.8
Steepness of land slope	*Tedafat*	Slope	66.7
Sedimentation at farm bottoms	*Delel*	Sediment	33.3
Surface stoniness	*Yedingay kimichit*	Stone litter	18.4
Rock exposure	*Nitaf dingay*	Rocky outcrop	22.4
Water color change	*Chickama woha*	Muddy water	25.9

used by farmers to examine the occurrence of soil erosion on farmlands. When farmers see stunted crop growth, they understand that there is deficiency of plant food caused by soil erosion and take measures to restore the lost nutrients by adding either chemical fertilizers or animal manure. For instance, Table 4 indicates that about 71% of the farmers applied manure on 221 plots (74.79 ha lands) in the year 2010/2011. However, the use of manure as a natural soil fertilizer has become endangered by its demand for fuel and by the shortage of livestock feed resources [see Belay and Bewket, 2013a].

Farmers also directly perceive the existence of soil erosion when crop seedlings are removed by water. This is an evident sign of soil erosion particularly on steep-lands. Poor crop growth and plant seedling removal by water were reported by about 69% and 55% of the farmers, correspondingly (Table 3). Comparing the trend of successive crop yields on the same land is another proxy indicator used by farmers to understand the presence of soil erosion on their farms. They usually compare the amount of yield obtained in the second year with that received during the first year, and they conclude that there is erosion if the amount of yield has decreased. This proxy indicator was used by over 73% of the farmers because farmers directly associate soil erosion with yield reduction i.e., with the loss of benefits. This is an essential indicator that initiates farmers to take conservation measures to reverse the situation. In such occasions, farmers usually use crop rotation, intercropping and improved seeds in addition to application of manure and chemical fertilizers. Crop rotation and inter-cropping were apparently applied by greater than 92 and 75% of the farmers, respectively (Table 4). During the field work, it was observed that cereal crops like *tef*, maize, millet and barely were planted in rotation with leguminous crops such as oil seeds, pulses and *gibto (Lupins termis)*.

Most of the land degradation indicators are almost similar to the report indicated Vigiak *et al*. [2005] in Tanzania and Okoba and Sterk [2006] in Kenya. Okoba and sterk [2006] indicated that indigenous soil erosion indicators are well in agreement with the broad scientific knowledge. The indigenous methods reported by the participant farmers were based on their perceived experiences, and these are not far from the already accepted scientific methodology. Farmers observe and apply the methods during their farming operations. Hence, they do not take much time to perceive and easily reverse using simple measures. As the farmers detect and reverse observed erosion signs by themselves, there is no need of intervention and convincing what methods to choose and how to apply the preferred methods. They take an action by themselves immediately when they see the danger. Okoba and sterk [2006] indicate that such current erosion signs are easily obliterated and reversed. Efforts have thus to be done by the concerned agencies to enhance these inbuilt farmer practices.

Introduced methods such as chemical fertilizer and improved seeds are applied

Table 4. Soil fertility retention and SWC measures reported by farmers in three RKAs (Badani, Dubi and Gayta) for year 2010/2011

SWC practices	Size performed	N° of plots treated	Size treated (ha)	Reporters (%)
Manure	–	221	74.79	71
Crop rotation	–	–	–	92.5
Inter-cropping	–	–	–	75
Chemical fertilizer (kg)	34,308.5	467	188.5	76.1
Improved seed (kg)	1658.5	184	72.9	70.65
Live fences (N° of trees)	16,283	121	39.3	40

to increase yield for short-term benefits and they are appraised for their immediate advantage and higher productivity. Some 467 plots measuring over 188 ha were treated with 34,308.5 kg fertilizers (Urea and DAP/Di-Ammonium Phosphate) on over 76% of the farmers' fields in 2010/2011 (Table 4). In FG discussions, farmers were complaining and blaming on use of fertilizer on the ground of high cost and on only one time use. Most farmers complain chemical fertilizer is too expensive to afford. Tefera and Sterk [2010] reported that 41–50% of the farmers in the Fincha'a watershed, western Ethiopia, add chemical fertilizer and collect better yields, but they complain on the higher costs. This finding is thus in line with the result reported in Tefera and Sterk [2010]. A significant number of farmers complained that the use of chemical fertilizer exhausts the long-term fertility of land. They explained that a land planted using fertilizer in the first harvest will never give good yield without fertilizer use in the next harvest. During FG discussions, more than half of the participants commented that urea creates a hard crust on their farms. Similar complaints were also reported in Beyene *et al.* [2006] in Tigray, northern Ethiopia.

Improved maize seeds were used by about 71% of the farmers in 2010/2011 cropping year. Some 1658.5 kgs of improved seed were applied on 184 plots covering 73 ha (Table 4). But, they were blamed for their one-time service because the crop obtained using improved seed in the first harvest cannot be used as a seed in the next harvest. This has forced the farmers to search for new seeds from seed trading enterprises and make them dependent on purchased seeds. In FG discussions, it was learned that seed for the next harvest was kept from yield obtained at home or from the surrounding villages and farmers were not involved in search of seed when the sewing season approaches before the expansion of external seed application. But now, farmers spend part of their time in search of seed and other inputs. The seed accessed through such efforts was also observed sometimes to fail to germinate or to grow as expected. This condition has worried farmers of the study areas, particularly in 2010/2011 main cropping season. Farmers reported that maize seed (BH660) accessed from a seed enterprise at Bahir-Dar, northwest Ethiopia, was failed to germinate and to grow well. They were; therefore, subjected to additional cost of money and labor to replace the lost crop in RKAs named Dubi and Gayta. Adato and Meinzen-Dick [2002] reported that improved maize varieties in Mexico were more vulnerable to pests and decaying and farmers in Zimbabwe who had adopted hybrid maize were vulnerable to widespread crop losses and loan defaults due to susceptibility of the new maize to drought and fertilizer burn in the early 1990s. The problem encountered by farmers in the study areas has thus support from other areas worldwide.

A significant number of farmers have reported that introduced seeds caused the loss of indigenous crop varieties from their farms and crop stocks. According to the reports (Table 5), maize varieties locally named *dimishumbi* (red maize), and *zagir/ageriche* (indigenous maize) were on the verge of disappearance. About 55% of the participants indicated that *Zagir* has lost from their farms and from their crop stocks beginning from 2004 and 23% of them reported *dimishumbi* has disappeared from 1998 onwards. The mentioned maize varieties are preferred in the area mainly for their sweet taste and preparation of the local traditional drink named *tella (*local bear*)*.

Table 5. Maize crop varieties lost from smallholder farms (% of reporting farmers)

Local name	English name	Reporting farmers (%)	Time (year)
Dimishumbi	Red maize	23	since 1998
Zagir/Ageriche	Indigenous maize	55	since 2004

The above cited evidences indicate that a significant number of farmers used to depend on purchased seed that may sometimes be difficult to access due to shortage or inability

Fig. 2. Farming in Abadira (Oct. 2012).

to afford the required market level costs. In some occasions, the seed shortage may cause failure to cultivate available land and may also lead to food insecurity. The loss of the indigenous maize (*zagir/agerich*) from the stock of 55% farmers meant that the crop would gradually disappear from the area. This eventually could cause the risk of genetic erosion. Heal *et al.* [2004], remarked that a turn down in genetic diversity in agriculture can lead to susceptibility to pathogens, and cause the risk of crop failure and problem of food supplies. Visser [1998] has also indicated the rise of modern breeding industries during the green revolution have caused the shift from many locally adapted varied landraces to fewer high-input demanding external varieties. The focus on only external crop varieties with neglect of indigenous ones may lead to the loss of indigenous genetic resources like what was happened in Greece, India, and other Southeast Asian countries after the 1960s as cited in Visser [1998] and Heal *et al.* [2004].

The continuously growing fertilizer price is also another frequent headache to farmers. Dependence on external input degrades the

Fig. 3. SWC measures adopted by farmers in micro-watersheds (Oct. 2012)

confidence of farmers to use local resources and indigenous methods. Takeuchi and Shaw [2008], for example remarked that the reliance on introduced technology make farmers to be expectant of external resources and methods and erode their self-esteem to assist themselves. Farmers who use only chemical fertilizer and government seed frustrated and worried when the sewing season approaches. Shortage of supply including lack of the necessary money to buy seed and inputs make them much worried and frustrated. Takeuchi and Shaw [2008] thus advice the ideal LWM measure ought to incorporate the 'right mixes' of local and introduced methods.

SLWM measures practiced by farmers in the study RKAs include also contour farming, traditional ditches and unplowed farm strips. Contour farming (Fig. 2) is a commonly used traditional practice exercised by farmers in the study RKAs as elsewhere in Ethiopia. In the study RKAs, farm lands are usually ploughed three to seven times depending on the type of soil, requirement of the specific crop and availability of draught power and labor. Nevertheless, as Bewket [2003] notes repeated farming prepares the soil to further erosion. Nyssen *et al.* [2000] also remarked that traditional contour ploughing practices initiate down-slope soil movement and accumulation of soil in the lower farm margins. Therefore, there is a need to assess the benefits and adverse effects of the traditional practice of repeated ploughing. Traditional ditches are usually applied on newly plowed farms immediately after sewing. They are used to drain-out excess water on water-lodged soils. During the field survey, traditional ditches were recorded on about 52% of the assessed farms (Table 2). Unplowed farm strips were often observed between the boundaries of farms owned by different people. Grass and bushes grow along these strips and trap eroded soil materials.

In recent years, installations of structural SWC measures (Fig. 3) have been going on through community-based campaigns on micro-watersheds. For instance, in 2011/2012 alone, over 152 km soil bunds were constructed on 968 farm plots measuring 758 ha lands in the four RKAs (Table 6). Soil-bunds measuring some 22 kms were also constructed on 6 community grazing fields measuring 219 ha. Stone-bunds measuring 2 km were installed on 20 plots of 10 ha lands and other 2 km stone-bunds were built on three grazing fields measuring 10 ha lands. Over 53 km soil-bunds and 2 km stone-bunds on farmlands and over 11 km soil-bunds and some 2.2 km

Table 6. SWC structures built by farmer campaigns in micro-watersheds in the four RKA (2011/2012)

Structure type	Size covered
Soil-bunds on farm lands	
Size executed (km)	152.3
N° of plots treated	968
Size of plots treated (ha)	757.5
Size stabilized with vegetation (km)	53.5
Length maintained (kms)	144
Soil-bunds on grazing lands	
Size executed (km)	22
N° of fields treated	6
Size of fields treated (ha)	219
Size stabilized with vegetation (km)	11.3
Length maintained (km)	12.5
Stone-bunds on farm lands	
Size executed (km)	1.85
N° of farms treated	20
Size of fields treated (ha)	10
Size stabilized with vegetation (km)	1.85
Length maintained (km)	1.85
Stone-bunds on grazing lands	
Size executed (km)	2.2
N° of fields treated	3
Size of fields treated (ha)	10
Size stabilized with vegetation (km)	2.2
Length maintained (km)	2
N° of Gullies stabilized	
Gullies treated with check dams	22
Gullies stabilized with vegetation	12
Gullies maintained	14

Source: RKA offices in the study areas (Oct. 2012) stone-bunds on grazing fields were stabilized with vegetative measures. Previously installed 144 km soil-bunds and 2 km stone-bunds on farmlands and over 12 km soil-bunds plus 2 km stone-bunds on grazing fields were also maintained in the four RKAs in 2012. In addition, new check-dams were constructed on 22 gullies and old check dams were maintained on another 14 gullies. Gullies stabilized with vegetation were found 12.

The above SWC structures were executed through farmer participatory approaches operated in mass mobilization campaigns (similar to what was happening before the 1990s). The farmers' campaigns were carried out for a period of 20–40 days during the dry months using free farmer labour. Similar SWC measures were reported implemented in central Ethiopia during the Derg time (1975–1990) through farmer campaigns assisted by FFW program [Shiferaw and Holden, 1998]. But, such projects were only partially successful or else ended in failure due to their dependence on forced labour as reported in previous studies [e.g. see. Shiferaw; Holden, 1998; Amsalu, 2006].

Integrated application of technologies

Research evidence recommends the use of integrated measures such as local and new practices, structural and vegetative measures, run-off control and yield enhancing technologies in the fields of sustainable land management (SLM) and agricultural activities [Erkossa and Ayele, 2003]. Many studies remark that neither animal manure nor chemical fertilizer alone will improve soil fertility and most recommend the integrated use of organic and inorganic inputs [Damisa and Igonoh, 2007] such as manure, chemical fertilizer, mulch, intercropping, cereal legume rotation and green manure.

Many farmers in the study RKAs were observed using integrated SWC technologies such as structural and vegetative, indigenous and introduced measures. For instance, farmers used contour farming for longer years accompanied by traditional ditches, farm boundary, cut off drains, stone-bunds, and live-fences to conserve soil and water. They were able to mix indigenous and introduced soil fertility methods on the same plot. About 20% of the farmers integrated manure with compost, Urea and DAP and achieved excellent results. Other combinations also reportedly showed good results (Table 7). Generally, farming households were able to get good results by integrating a number of indigenous methods with introduced ones. Erkossa and Ayele [2003] reported that manure and fertilizer were used together on the same field in western Ethiopia. This supports the current study. According to Osman *et al.* [2000], the use of integrated SLM technologies helps farmers to diversify farming activities, to minimize production risks and to reduce soil erosion hazard. The use of integrated methods such as local and introduced practices, rainfall and irrigation, crop and livestock is thus beneficial.

Table 7. Indigenous and introduced land management technologies integrated by farmers

SWC & soil fertility technologies		Result	% of reporters (n = 201)
Indi-genous	Introduced		
Manure	Urea + DAP + Compost	Excellent	20
Manure	Urea + Lime + Compost	Good	22
Manure	DAP	Good	22

STAKEHOLDER LINKAGES FOR SUSTAINABLE LAND MANAGEMENT

Amsalu [2006] noted that household level LWM decisions tend to be influenced by village, national and regional level authorities. This influence is also reflected in the study areas. Decisions made at federal/regional levels have been influencing household technology adoption decisions. Farmer participation in new technology identification decisions are observed very low (2%). Only 20% of the farmers participate in technology use related trainings at both local and Regional levels. The mean farmer-DA contact regarding LWM issues is observed very low, < one day per annum. Generally, farmer-expert linkages are found getting weaker from RKA to district and regional levels (Table 8).

Table 8. Farmer-expert linkages in SWC activities

Farmers' interactions & participations	Responses in % (n = 201)	
	Yes	No
Contact with RKA officers	85	15
Contacts with DAs	76	24
Contacts with District level experts	18	82
Contacts with Zone level experts	6	94
Contacts with Region level experts	4	96
Participation in training at different levels*	20	80
Participation in new technology selection decisions	2	98
Frequency of contact with DAs (average N° of days yr^{-1})	0.98	–

Source: Adapted from Belay and Bewket [2013c]
*RKA, District, Zone and Region levels

FARMERS' LIVELIHOOD ASSETS AND STRATEGIES

Livelihood assets

A household survey in three RKAs (Tables 9 &10) indicate that age, sex, education, and family size are important human-demographic assets that enable rural households to produce livelihood goods in the study RKAs. Some 15% of the studied households were led by females. The mean age of all farmers interviewed was 39.6 years. The average number of family members was discovered 5.61. The active productive age group in the surveyed population was calculated 48% while the rest 49% were below age 18 and people above age 64 accounted for 3% of the total (Table 9).

Table 9. Household demography (%)

Household heads by age and sex				Total population of sample households by age and sex			
Sex			Total	Sex			Total
Age	M	F		Age	M	F	
18–35	35	13	32	<18	49	49	49
36–64	57	77	60	18–64	48	49	48
>64	8	10	8	>64	3	2	3
Total	100	100	100	Total	100	100	100

Source: Belay and Bewket [2013a].

Land and livestock are also among the most important resources used by farmers to produce livelihood items (Table 10). Getting professional support from DAs and agricultural experts (Table 8), taking credit from ACSI (Amhara Credit and Savings Institution), using irrigation, charcoal and wood selling, engagement in daily labor and sharecropping (Fig. 4) were among the livelihood strategies used by farmers to improve their livelihood conditions. Intercropping, crop rotation, using improved seeds, adding animal dung and industrial fertilizer were also among the methods used by participant farmers to increase crop yields (Table 4).

Table 10. Mean livelihood assets among the surveyed households in three RKAs

Household assets	Mean values (n = 201)
Age of household heads (years)	39.61
Level of education (years)	1.29
Family size (number)	5.61
Farm size (ha)	1.42
Land/man ratio (ha $person^{-1}$)	0.28
Livestock (TLU)	3.66
Round trip plot distance from home (km)	1.32

Source: Adapted from Belay and Bewket [2013a]

Land is the principal natural asset from which human beings derive their basic livelihood needs such as food, clothing and shelter. Farmland is the basic asset from which farmers in the study RKAs produce food supplies. But its size is diminishing from time to time due

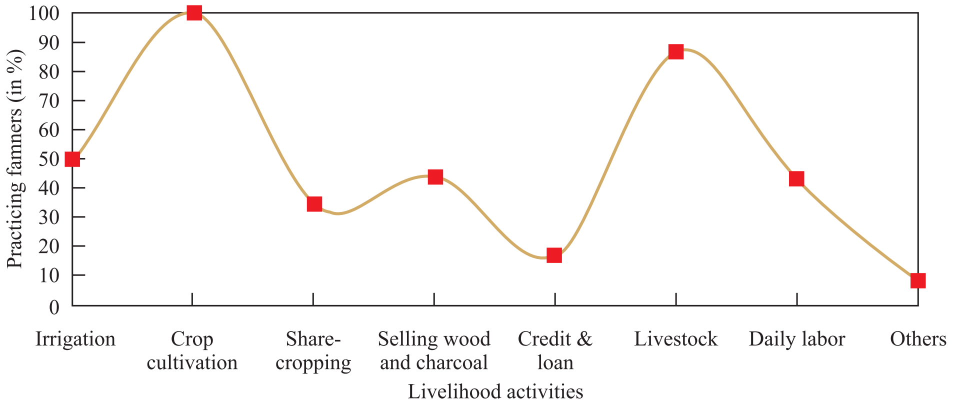

Fig. 4. Farmers' livelihood strategies

to increasing populations. The mean farm size in the study areas was 1.42 ha per household and 0.28 ha per person. The mentioned farm size is also not available for some portion of the households (for about 14%) in the three RKAs [see Belay and Bewket, 2013c] and it is fragmented and faraway from the homesteads wherever it is available, demanding a 1.3 km roundtrip trail distance on average (Table 10). However, walking farther distance from homesteads to work on the farms was found significantly reducing households' sustainable land management technology adoption decisions and practices like manure use as reported in Belay and Bewket [2013a].

Livestock are part of the major farming enterprises in the study RKAs like that elsewhere in rural Ethiopia and form the second major activity next to crop farming. They provide farming families with draught power, manure, cash revenue and food items (milk and meat products). Culturally, livestock heads constitute a prestige value and they are indicators of wealth status in the rural areas. Around 87% of the farmers interviewed reported that they have livestock (Fig. 4). The mean household livestock holding (in tropical livestock unit, TLU) was about 3.66 (Table 10). Livestock are essential assets that enable farmers' to enhance sustainable technology adoption decisions and to improve household livelihoods [see Belay and Bewket, 2013a].

Around 17.4% of the studied households were users of rural credit from ACSI and farmers' cooperatives (Fig. 4). Farming households were also receiving professional support from DAs and agricultural experts. However, average annual farmer-expert contacts were < 1 day (Table 8).

Livelihood strategies

Farmers in the study RKAs have various income sources and livelihood strategies to cope-up with challenges. Crop-livestock mixed farming is the major occupation of over 85% of the farmers studied. Crop production is the main source of income for almost over 99% of the farmers (Fig. 4). As shown in Table 11, the mean crop income received by each household in 2010/2011 was ETB 3244. The highest income was derived from maize production and followed by *tef* and potato. The lowest mean income was generated from pulses and oil seeds.

The income earned from farming and livestock rearing is not sufficient to cover all household expenses. Therefore, it is supplemented by income derived from selling wood and charcoal, daily labor, taking credit and loan and other activities (trading, weaving, carpentry, tannery and receiving remittance). These activities correspondingly serve as sources of additional revenue for 44, 43, 17 and 8% of the farmers (Fig. 4). Other

Table 11. Mean crop income of farmers' in three RKAs in 2010/2011

Crop type	Mean income ETB*
Tef	596
Maize	1063
Barely	317
Millet	175
Pulses	4
Oil seeds	57
Fruits	74
Vegetables	216
Potato	590
Sugar-cane	153
Total	3,244

* ETB 16.50 = USD$1 during the time of survey
Source: Field survey (April 2011–October 2012)

livelihood sources mentioned by farmers also include sharecropping and irrigation.

Some 34% households in the study rural communities relied on sharecropped land which provided them with considerable food supplies (Fig. 4). Table 12 indicates that 399 farmers in the four RKAs were sharing-in land from 368 other farmers in 2011/2012. Around 552 plots (121.5 ha lands) were transacted in the process. Some 37 farmers leased-out about 38 plots (11.56 ha lands) costing a total of ETB 141450 to other 36 persons for 25 years. The average cost of the sold farms was ETB 12,236 ha^{-1} or 3,722 $plot^{-1}$. Each household has sold at least one of his/her plots (0.31 ha lands). Over 44% farmers who rented-out their land were women but only one was female among who rented-in land. Most of the farms leased for 25 years were checked planted eucalyptus trees which may lead the soils to be acidic. The bulk of the leased and sharecropped farms were not often treated with proper SWC structures and most of them get exhausted their potential after continuous and repeated tillage with no treatments.

Participation in irrigation in the study areas enabled some farmers to grow diverse crops including vegetables. Table 13 shows that

Table 12. Sharecropping and long-term land leases in the four RKAs (2011/2012)

Information type	Value
No of sharecropped plots (2011/2012)	552
No of farmers who rent-out their land to others (2011/2012)	368
No of farmers who rent-in land from others (2011/2012)	399
Total size of sharecropped plots in 2011/2012 (ha)	121.5
No of farmers who leased out their land for 10–25 years	37
No of farmers who leased-in for 25 years	36
Size of farms leased for 25 years (ha)	11.56
Number of farms for long -term	38
Total land cost ETB	141450
Mean cost ETB per ha	12,236
Mean cost per plot ETB	3,722

Source: RKA offices of the study areas (Oct. 2012)

over 30% of the farmers (22% in Abadira, 4% in Badani, 31% in Dubi and 72% in Gayta) were practicing irrigation in 2010/2011. The proportion of farmers participating in irrigation appears larger in Gayta and lower in Badani. Some 46 streams (9, 8, 14 and 15 in Abadira, Badani, Dubi and Gayta, respectively) were identified during the field work of which 74% (70, 50, 64 and 93 in Abadira, Badani, Dubi and Gayta, correspondingly) were used for irrigation. A total of 44 diversion canals and 34 water committees with mean number of 5 members were observed supporting the irrigation scheme in the study areas. Some 1372 plots were irrigated and around 25 farmers were sharing one diversion canal on average. Irrigation water in the study RKAs was distributed in rotation turns and was managed by an elected water agent named *axu tabla* (the father of water).

Since the past decade, farm land has been shrinking in the study RKAs due to increased population pressure and pressed farmers to grow diverse crops (cereals, vegetables and fruits) and become a "push factor" as what was termed in Barrett *et al.* [2001] for diversification

Table 13. Land use information by RKAs (2010/2011)

Information type	Abadira	Badani	Dubi	Gayta	Sum
No of streams	9	8	14	15	46
No of irrigated streams	7	4	9	14	34
% of irrigated streams	78	50	64	93	74
No of diversion canals	17	4	9	14	44
No of water committees	9	2	9	14	34
No of members in each committee	3	6	4	7	5
Total N° of farm HHs	1350	481	698	814	3343
% of HHs participated in irrigation	22	4	31	72	33
No of HHs participated in irrigation	297	20	218	584	1119
No of irrigated plots	297	20	275	780	1372
No of HHs per diversion canal	17	5	24	42	25

Source: RKA offices of the study areas (February 2011 & Oct. 2012)

of livelihood activities. Farmers with non-or-small sized plots were also forced to search for alternative income generating activities such as daily labor, charcoal production and wood selling. For instance, the LSDI (Fig. 5) indicates that farmers have been able to diversify their livestock and cereal production and off-farm activities in all of the study RKAs. Nevertheless, pulse and oil seed production were not sufficiently diversified and were almost dominated by only one crop. As to Barrett *et al.* [2001], livelihood diversification can be considered as a "self-insurance" to minimize risk factors. In his view, off-farm income is a "pathway" for rural farmers to escape from poverty and hunger. Diversifying livelihood strategies is thus an important issue to be encouraged in the study areas.

THE NEED TO BUILD ON LOCAL SUSTAINABLE LAND MANAGEMENT PRACTICES

Generally the low level of success in SLM projects is caused to some extent by attempts to use technologies unsuitable to particular environmental and socioeconomic circumstances of the project sites. It has been proven elsewhere that SLM technologies can only be successfully implemented if it is suitable for the particular conditions of a site. Similarly, research evidence has also shown that a technology which is the development or

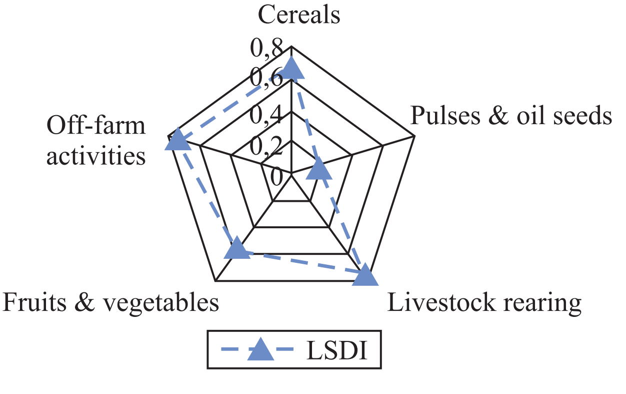

Fig. 5. Livelihood strategy diversification index (LSDI)

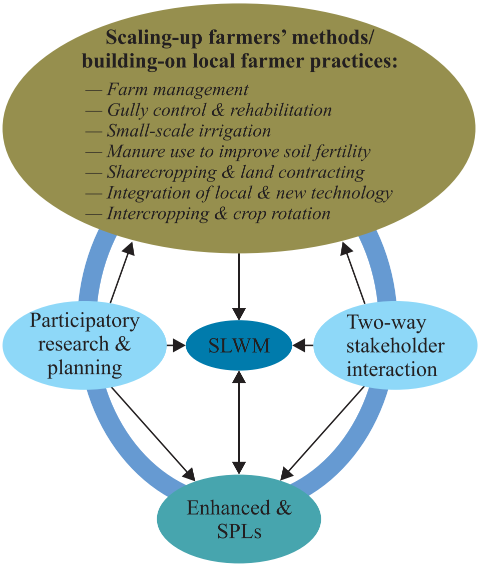

Fig. 6. Framework for enhancing rural livelihoods through SLWM

improvement of an existing practice is usually accepted more readily than something which is completely new, because of the fact that the former are technologies that are built upon local traditional practices and hence local skills and knowledge. In other words, consideration of suitability of technologies to local agro-ecological and socioeconomic circumstances contributes to the success of interventions. This underscores the need for future interventions to pursue participatory planning and farmer-led processes for a systematic integration of indigenous knowledge with modern technical knowledge to arrive at environmentally and socially sensitive technologies and practices encompassing not only watershed rehabilitation goals, but also social benefits in terms of immediate returns to the participating households. SLM practices required to enhance rural livelihoods thus should be emanated from building on local practices, integration of local and conventional technologies, and through promoting two-way stakeholder interaction systems and mapping and documenting land management information (Fig. 6).

Farmer participation must be considered as a key factor in building on local practices. This is because most of the land and water use and management decisions are made by the farmers. It is learned from past literatures that SWC interventions that neglected farmers' involvement in decisions were doomed to failure or offered limited success [Amsalu, 2006]. The previous top-down blanket technology promotion approaches exercised in the area had to give way to more farmer participatory trends that could enable farmers to reach appropriate land use decisions.

In two-way participatory stakeholder linkages both farmers and agricultural experts as well as researchers work in close collaboration, share experiences and grow to be enduring partners [Scherr, 2000]. Land management experts and researchers can enhance technical skills and capacities of farmers and they can learn new local practices, methods and knowledge systems from the farmers. The participatory stakeholder linkage thus must be established on the firm foundation of enhancing technical skills and research capabilities of farmers by involving them in assessment of land and water management constraints, technologies and as decision makers in SLM practices. In such cases, farmers could be made to identify their own needs, priorities and constraints. In the process, they may accept or reject technologies by themselves based on their perceived preferences [Amede *et al.*, 2006]. When they become familiar about technologies, farmers internalize it and make it their own undertaking. Therefore, planners, researchers and extension workers should put farmers at the centre of SLM [Shaxson *et al.*, 1989] to successfully scale-up best practices.

CONCLUSIONS

This paper was intended at assessing farmers' methods of soil erosion identification, SLWMPs, livelihood assets and strategies, in four RKAs in the northwestern highlands of Ethiopia. Participatory transect walks, field observations, examination of office documents and archives, formal and informal discussions with farmers' and FGs and structured household surveys of 201 rural households were the sources of data for the study. Results indicated that famers use around 13 indigenous methods to identify the occurrence of soil erosion on their farmlands. Over 79% of the studied farmers indicated the occurrence of soil erosion on their farmlands and some 59% reported the trend was increasing for twenty years, 1991–2011. More than 174 km soil-bunds and greater than 4 km stone-bunds were built on farmlands and degraded grazing fields through farmer participatory watershed development campaigns. Some 34 degraded gullies were stabilized using check dams and vegetative measures. Around 71% of the households applied cattle manure on about 75 ha lands to enrich soil fertility. A total of 44 diversion canals and 34 water committees were established to facilitate irrigation activities of some 33% households.

Farmers benefited from integrating indigenous and introduced LWM technologies such as structural and vegetative measures, manure and chemical fertilizers. Many farmers get results ranging from moderate to excellent by combining manure with compost and Urea and DAP. However, introduced methods such as improved seed and fertilizer were commented unaffordable and unsustainable. Over eight livelihood strategies were used by people in the study areas. But the mixed crop-livestock farming was the main source of income for the majority of the rural households. Farmers used to grow diverse crop and livestock varieties and perform various off-farm activities to cope-up with livelihood challenges. It is concluded that farmers' inbuilt methods and practices (farm management and gully control, manure use and small-scale irrigation, crop-rotation and intercropping, integration of indigenous and new technologies, sharecropping and land contracts, participatory research and planning and two-way stakeholder interaction) should be encouraged to enhance rural livelihoods and achieve the anticipated green development. Increased effort has to be made by concerned agencies to help farmers own assets essential for household livelihoods and to diversify their livelihood strategies and to use SLWM technologies.

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Mehretie Belay Ferede graduated in July 1986 with BA degree in geography from Addis Ababa University, Ethiopia. He taught general geography courses in several senior high schools in Eritrea and Godjam, Ethiopia (1986-1999). He led a planning and engineering team authorized in managing educational projects at Zone level education office (March 1999-April 2002) and a district office of education (May 2002-March 2005). In 2007 he graduated with MA degree in Geography and Environmental Studies (with specialization in Land Management) from the Graduate School of Addis Ababa University. In July 2013 he received his PhD degree in Geography and Environmental Studies (with specialization in natural resource management and the environment) from the Graduate School of Addis Ababa University. He is now assistant professor of Geography and Environmental Studies at Debre-Markos University, Ethiopia, which he joined in June 2007. His research interest is in the fields of sustainable land and water management and rural livelihoods. He has published several papers in peer-reviewed journals.

Woldeamlak Bewket is Professor of Environmental Studies at Addis Ababa University, Ethiopia. His main research interests are soil erosion and conservation, integrated watershed management and adaptation to climate variability and climate change. He has published over 40 papers in peer-reviewed journals.

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EDITORIAL OFFICE

Lomonosov Moscow State University
Moscow 119991 Russia
Leninskie Gory,
Faculty of Geography, 2108a
Phone 7-495-9392923
Fax 7-495-9328836
E-mail: GESJournal@yandex.ru

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